Self-assembly and Nanotechnology 10.524

Lecture on
Microelectromechanical Systems (MEMS)
& NEMS

Instructor: Prof. Zhiyong Gu (Chemical Engineering)

April 24, 2013

NEMS and MEMS

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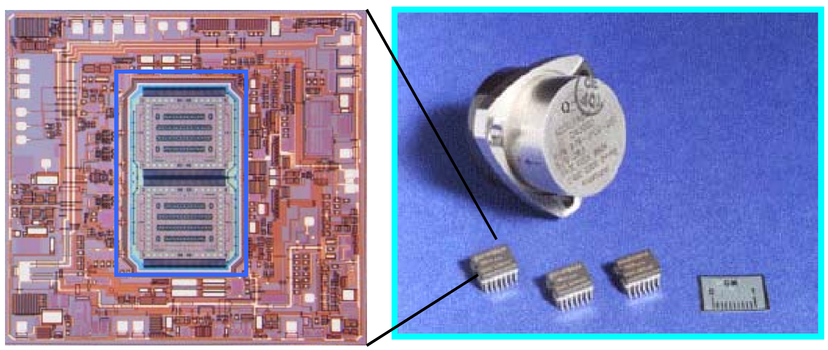
MEMS AND Microsystems

Lecturer: Dr. Hongwei Sun
Mechanical Engineering

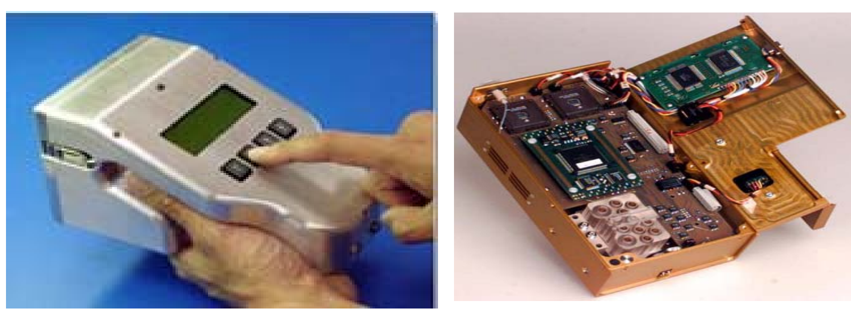
What is MEMS? Microsystems?

<u>MEMS:</u>
Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology.



Micro accelerometer and Comparison with Conventional one (Courtesy of NASA Glenn Research Center)

<u>Microsystems:</u>
Engineering systems that could contain MEMS components that are design to perform specific engineering functions



μChemLab™ by Sandia National Laboratory

Scale of MEMS and Microsystems

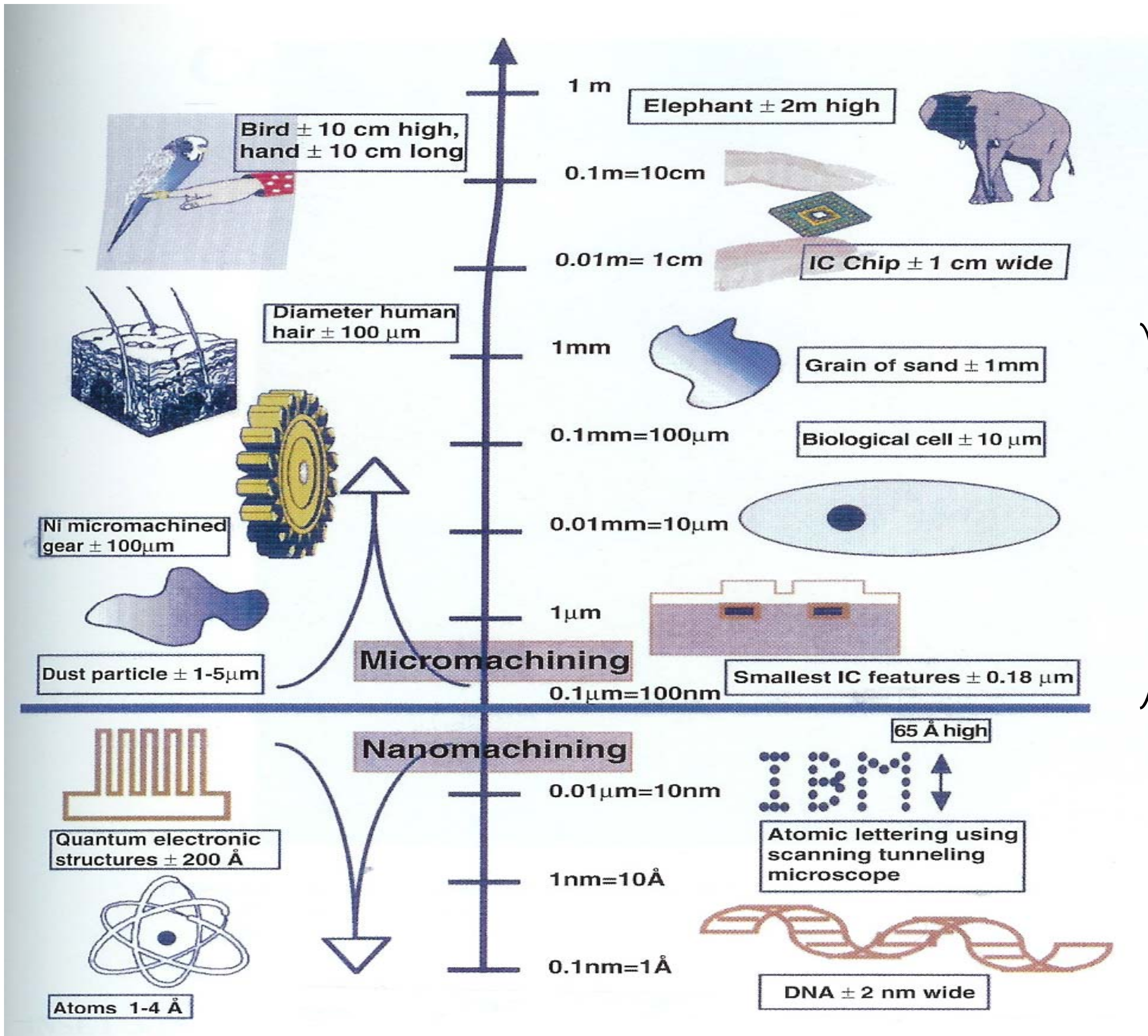


FIGURE 1.5 Various objects and their linear size.

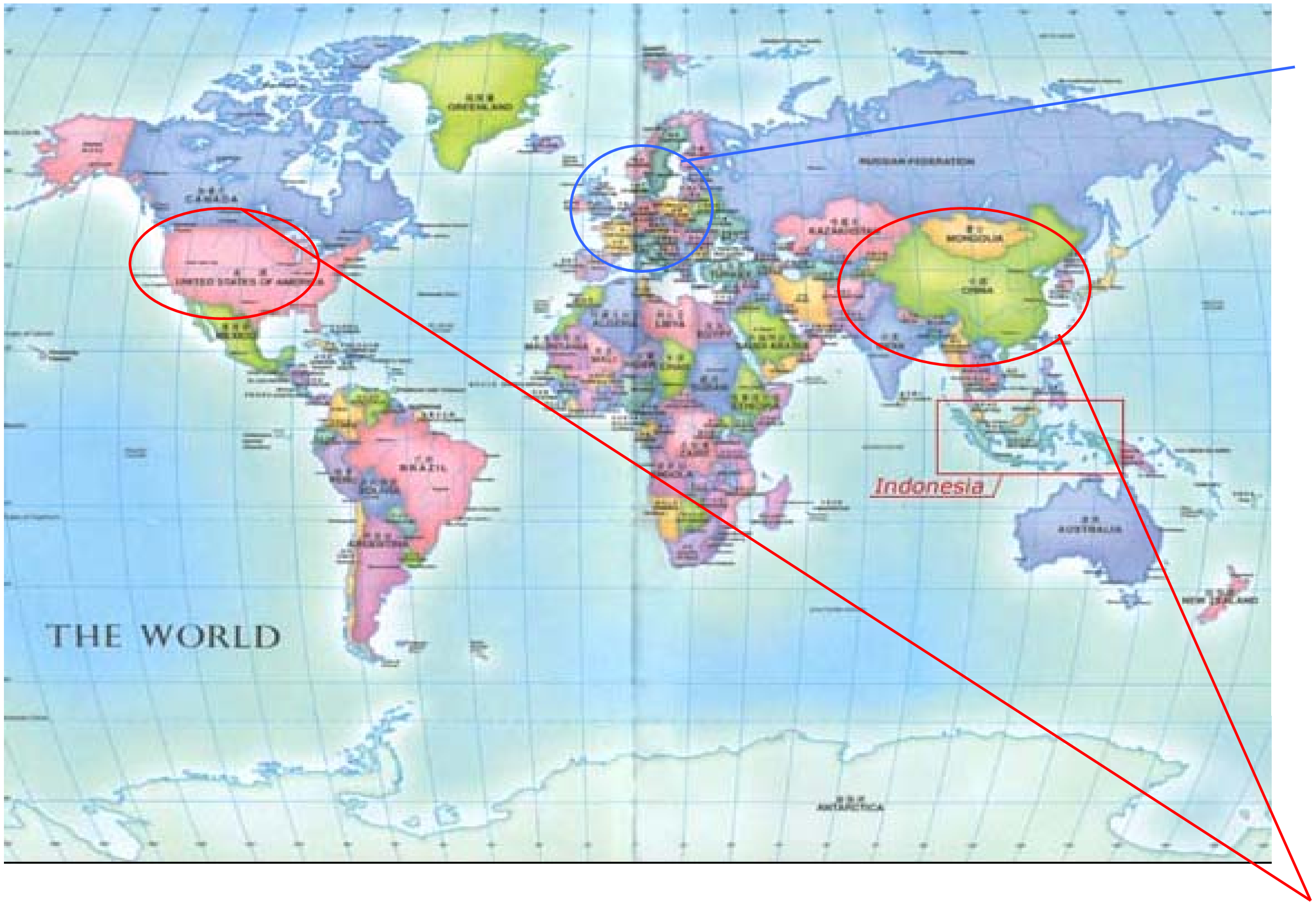
Microsystems

MEMS

Ant with MEMS Gear

Gear: 100um

Microsystems vs MEMS



Microsystems

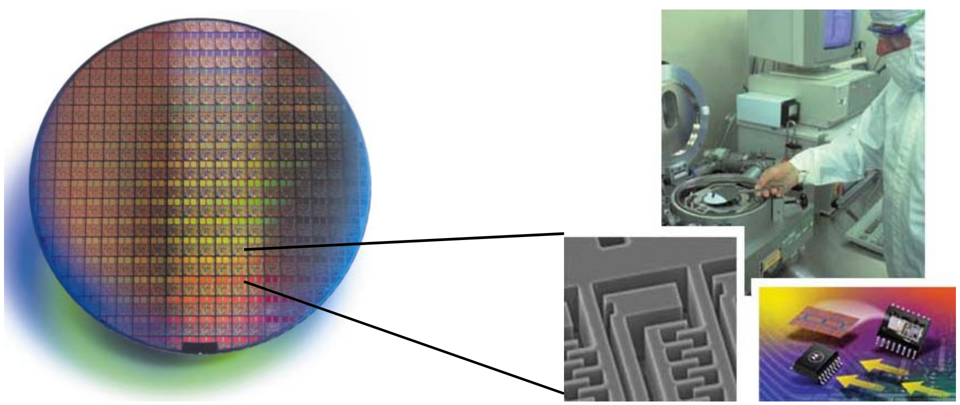
(Microelectromechanical Systems) MEMS

Micro/Nano technology development

	Topic	Knowledge Base	Work to Date	Leading Region
MEMS	components (for biosensing)	Advanced	Extensive	US ~ Japan ~ Europe
	integrated systems	Incomplete	Significant	Europe
	integration of biomaterials	Minimal	Isolated examples	Europe, US
Micro-fluidics	discrete devices	Advanced	Extensive	US
	integrated systems	Incomplete	Minor	Europe ~ US > Japan
Mass sensors	piezo devices	Advanced	Extensive	None
	Si cantilevers	Incomplete (esp. liquid operation)	Significant (dry) Minor (wet)	US ~ Europe
	integrated biomaterials	Incomplete	Significant	Europe ~ Japan
Nano-technology	"top-down" (nanofab.)	Incomplete	Significant	US > Europe
	"bottom-up" (molec. organized materials)	Incomplete	Extensive	US, Japan, Europe
	Integration into complex (bio)systems	Incomplete	Little	Europe ~ US

MicroElectroMechanical Systems (MEMS)

- ***Scale:*** from below 1 µm to above 1 mm
- ***Manufacture:*** batch fabrication technology
- ***Function:*** micro -mechanics, -electronics, -fluidics, -optics, …



Where MEMS is manufactured?

class	maximum number of particles per cubic foot of air of diameter greater than or equal to each indicated size					
	0.1 μm	0.2 μm	0.3 μm	0.5 μm	5.0 μm	
1	35	7.5	3	1	—	integrated circuits
10	350	75	30	10	—	
100	—	7502	300	100	—	miniature ball bearings; photo labs; medical implants
1000	—	—	—	1000	7	
10000	—	—	—	10000	70	color TV tubes; hospital operating room
100000	—	—	—	100000	700	ball bearings

MEMS Development flowchart

Design stage

Device/system design: mechanics, electronics, electrostatics, fluidics

System analysis: modeling, simulation

Process design: chemistry and physics of fabrication

Fabrication and integration

Fabrication: clean room

testing

Testing: scope, probe station, SEM, ...

Common Microfabrication techniques

Process Type	Examples
Lithography	photolithography, screen printing, electron-beam lithogaphy, x-ray lithography
Thin-Film Deposition	chemical vapor deposition (CVD), plasma-enhanced chemical vapor deposition (PECVD), sputtering, evaporation, spin-on application, plasma spraying, etc.
Electroplating	blanket and template-delimited electroplating of metals
Directed Deposition	electroplating, stereolithography, laser-driven chemical vapor deposition, screen printing, transfer printing
Etching	plasma etching, reactive-ion enhanced (RIE) etching, deep reactive ion etching (DRIE), wet chemical etching, electrochemical etching, etc.
Directed Etching	laser-assisted chemical etching (LACE)
Machining	drilling, milling, electric discharge machining (EDM), diamond turning, sawing, etc.
Bonding	fusion bonding, anodic bonding, adhesives, etc.
Surface Modification	wet chemical modification, plasma modification
Annealing	thermal annealing, laser annealing

Table of example processes used in micromachining.

MEMS vs. Microelectronics

Microelectronics	**MEMS**
Si, Si compounds, plastic	Si, Si compounds, plastic + polymer, metals, quartz…
Specific electric functions	Perform electrical, optical, mechanical, biological func.
Stationary!	Normally include moving parts!!!
Primarily 2-D structures	Complex 3-D structures
Complex patterns with high density	Relatively simple pattern
Non-contact with Media	Sensor is interfacing with contact media
Mature IC design methodology & standards	Lack of engineering design rule and standards
Fabrication techniques are mature	Not mature
Mass production	Custom-needs basis
Well established packaging technology	Infant stage

History of MEMS development

History of MEMS

1939 PN-junction semiconductor (W. Schottky)
1948 Transistor (J. Bardeen, W.H. Brattain, W. Shockley)
1954 Piezoresistive effect in semiconductors (C.S. Smith)
1958 First integrated circuit (IC) (J.S. Kilby)
1959 "There's Plenty of Room at the Bottom" (R. Feynman)
1962 Silicon integrated piezo actuators (O.N. Tufte, P.W. Chapman and D. Long)
1965 Surface micromachined FET accelerometer (H.C. Nathanson, R.A. Wickstrom)
1967 Anisotropic deep silicon etching (H.A. Waggener et al.)
1977 Silicon electrostatic accelerometer (Stanford)
1979 Integrated gas chromatograph (S.C. Terry, J.H. Jerman and J.B. Angell)

History of MEMS development

History of MEMS

1982 "Silicon as a Mechanical Material" (K. Petersen)

1983 Integrated pressure sensor (Honeywell)

1985 LIGA (W. Ehrfeld et al.)

1986 Silicon wafer bonding (M. Shimbo)

1988 Batch fabricated pressure sensors via wafer bonding (Nova Sensor)

1992 Bulk micromachining (SCREAM process, Cornell)

1993 Digital mirror display (Texas Instruments)

1994 Commercial surface micromachined accelerometer (Analog Devices)

1999 Optical network switch (Lucent)

Successful MEMS Products

- Automotive industry: manifold air pressure sensor, air bag sensor (accelerometer with self-test)
- TI digital mirror display (DMD) video projection system (development cost ~ $1B)
- Inkjet nozzles (HP, Canon, Lexmark) up to 1600 x 1600 resolution (~ 30M units per year)

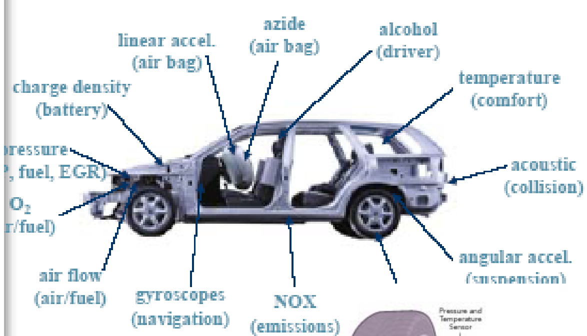
3. User-refillable cartridges can deliver 10-pl drops with a 10-µm drop-placement accuracy.

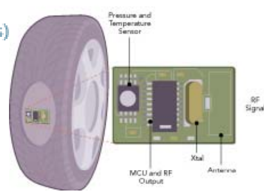
[J. Bryzek, 1998]

Applications of MEMS and Microsystems

MEMS/ Microsystems

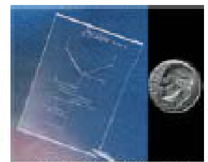
Automotive applications...



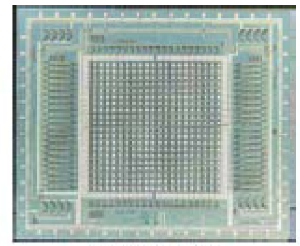


Biomedical...

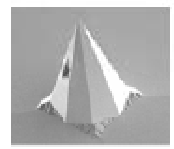
- Biochips, blood pressure sensing, genetic analysis, proteomics, diagnostics, drug delivery …



Disposable lab on a chip
(Caliper Technologies Inc.)



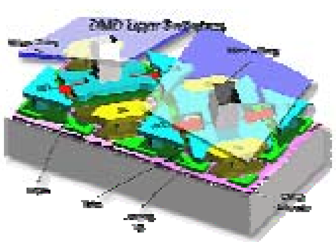
DNA Analysis chip
(Fabricated at Standard MEMS, Inc.)



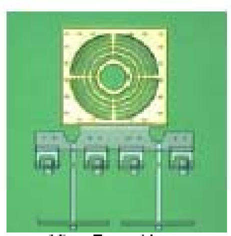
Microneedles
(Fabricated at Standard MEMS, Inc.)

Communications...

- Optical switching and routing, relays, wireless communication, information systems …



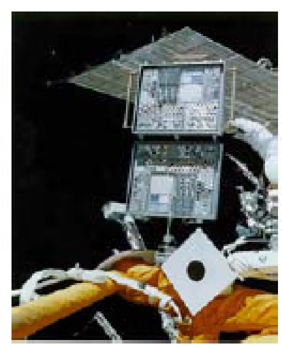
Digital Mirror Device (DMD) Light Switch
(Texas Instruments)

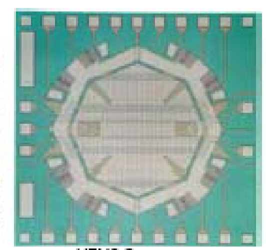


Micro-Fresnel Lens
(Fabricated at
Standard MEMS, Inc.)

Aerospace...

- Aircraft, micro-satellites, space exploration …





MEMS Gyroscope
(Fabricated at Standard MEMS, Inc.)

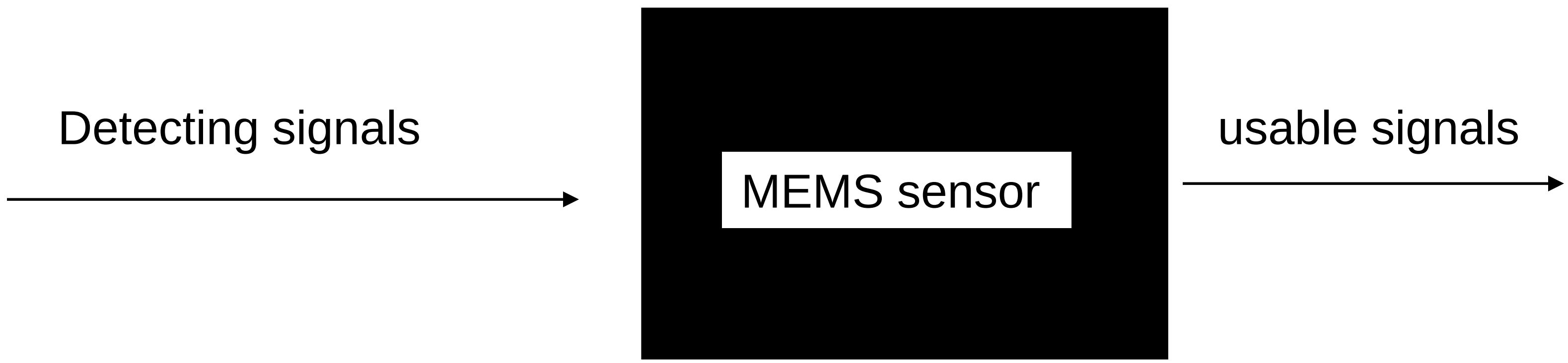
Market of MEMS and Microsystems

Roger Grace Associates

Application Sector	2000	2004	CAGR(%)
IT/Peripheral	8,700	13,400	11.5
Medical/Biochemical	2,400	7,400	32.5
Industrial/Automation	1,190	1,850	11.6
Telecommunications	130	3,650	128.1
Automotive	1,260	2,350	16.9
Environmental Monitoring	520	1,750	35.4
Total	**14,200**	**30,400**	**21.0**

(in Millions of US $)

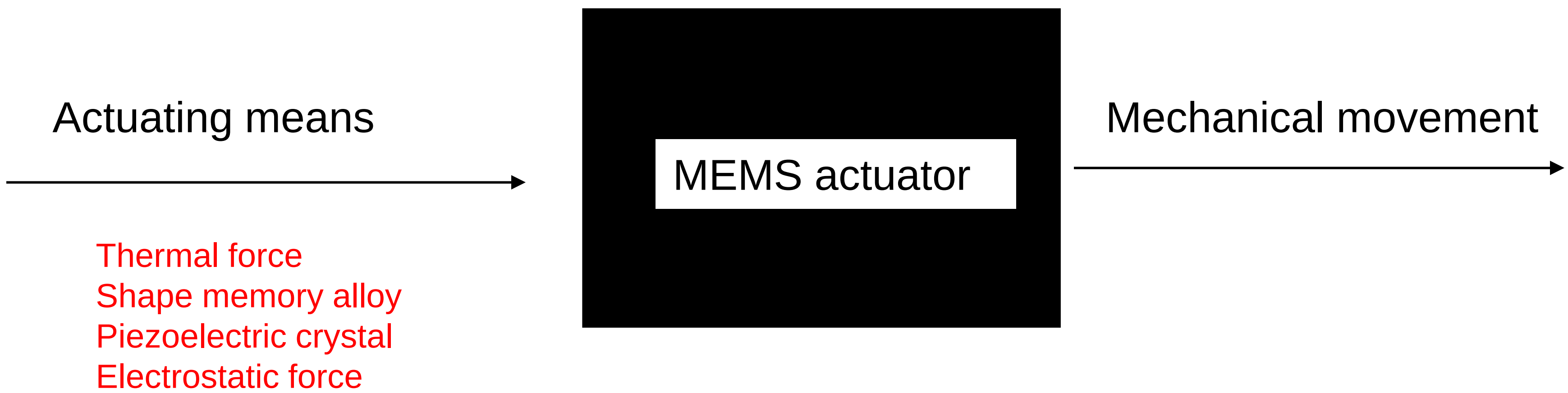
MEMS transducers (sensor & actuator)



Thermal--temperature, heat, heat flow
Mechanical--force, pressure, velocity, acceleration, position
Chemical--concentration, composition, reaction rate
Magnetic--field intensity, flux density, magnetization
Optic--intensity, wavelength, polarization, phase
Electrical--voltage, current, charge

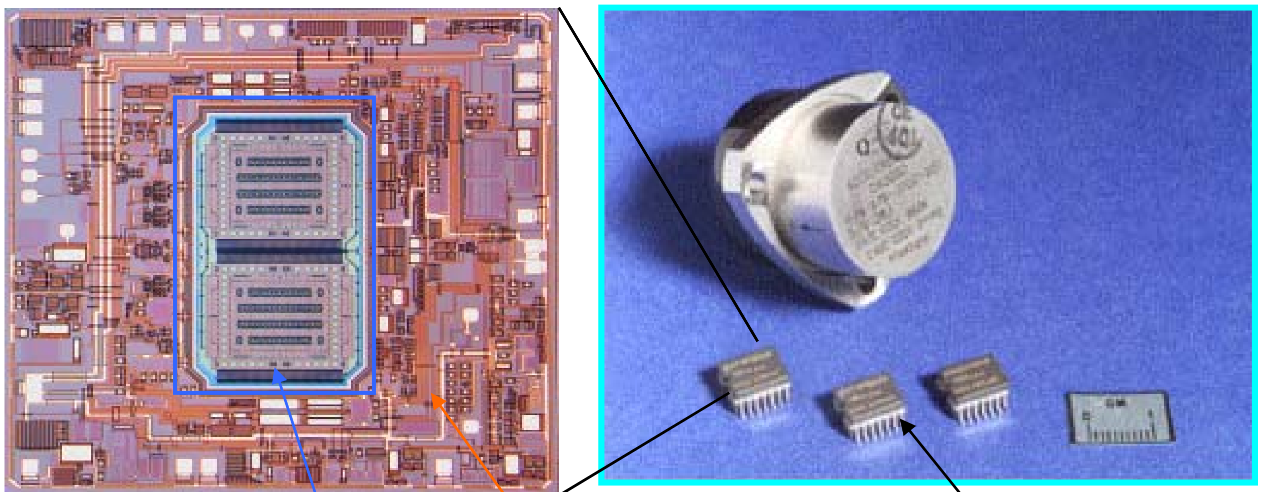
Electrical– voltage, current

MEMS transducers (sensor & actuator)

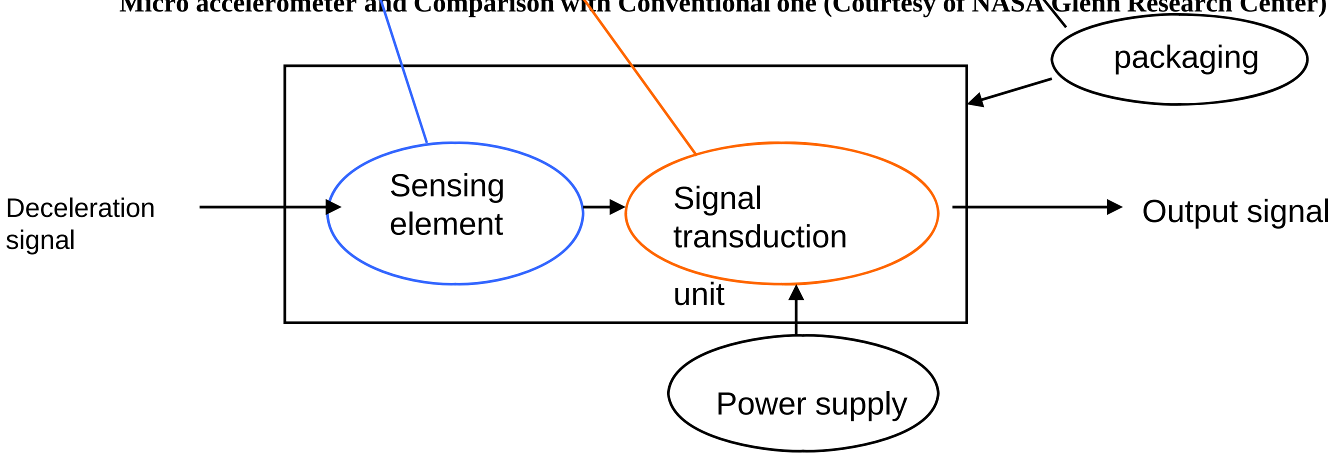


Typical MEMS/Microsystems-accelerometer

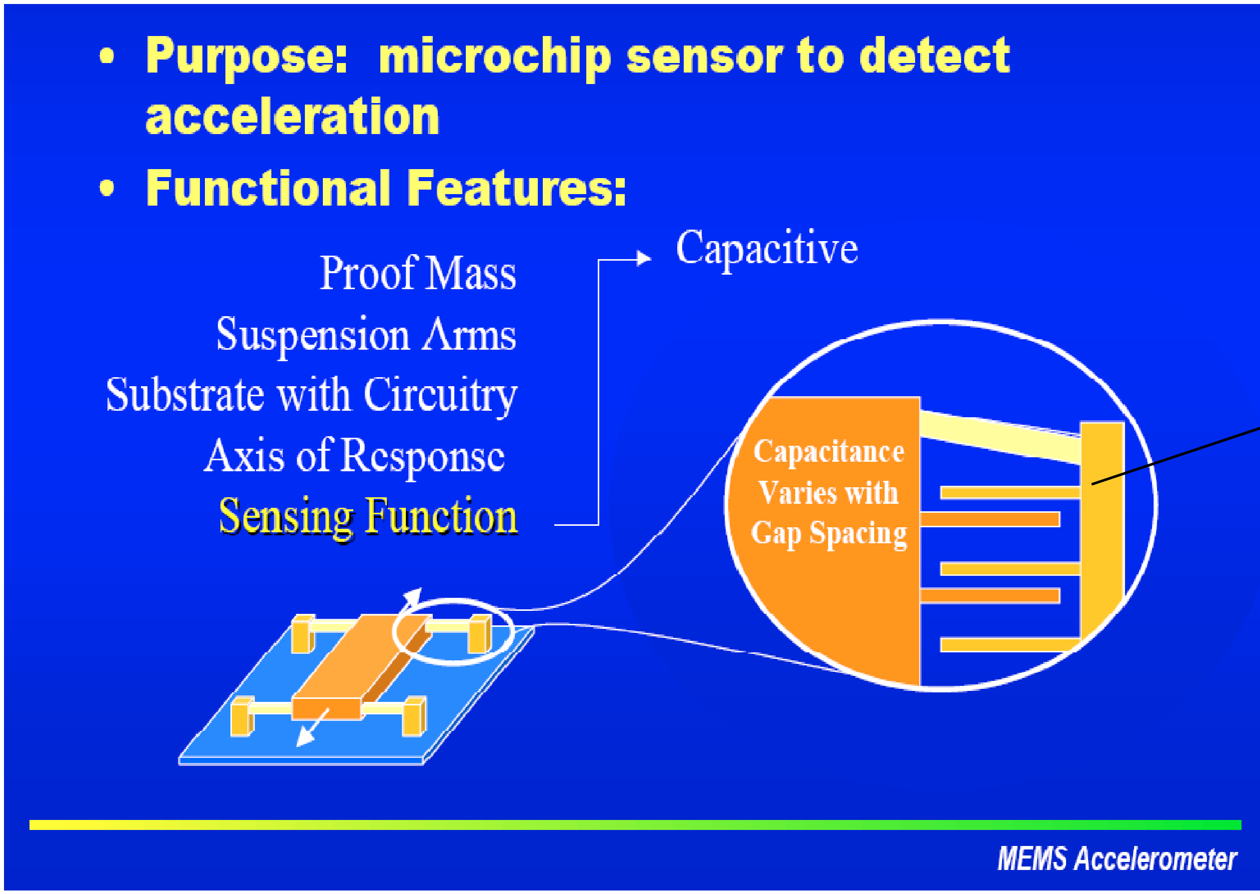
MEMS sensor:

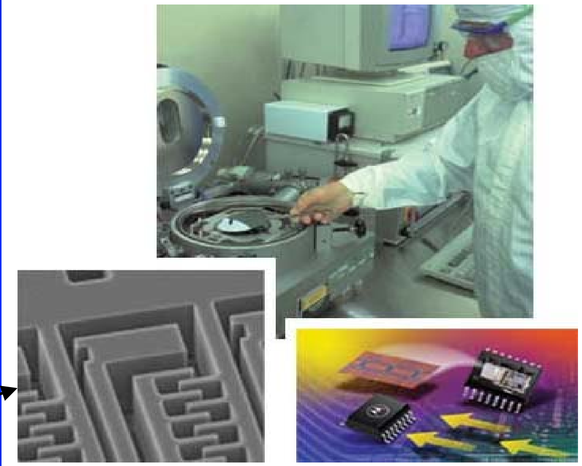


Micro accelerometer and Comparison with Conventional one (Courtesy of NASA Glenn Research Center)



Typical MEMS/Microsystems-accelerometer

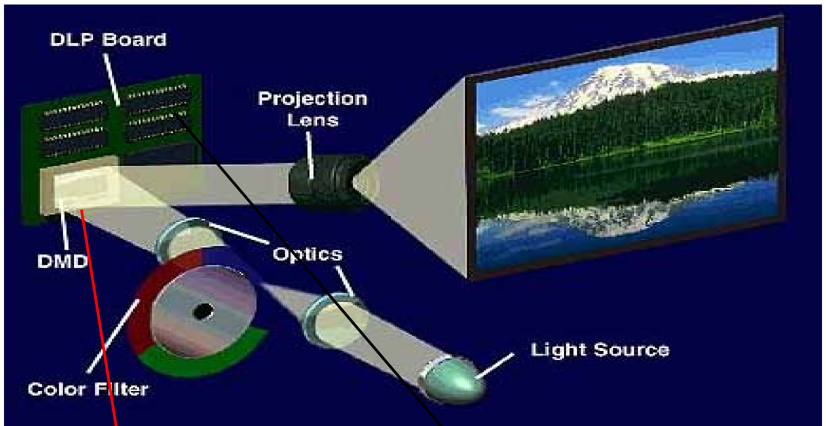


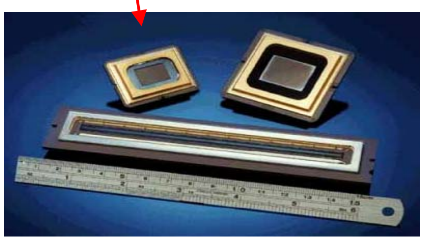


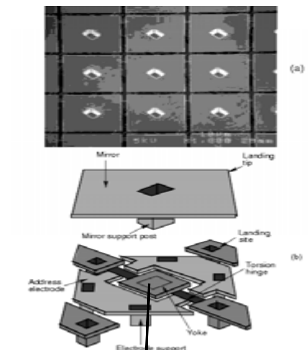
Conastantine, Friedman & Goldberg

Typical MEMS-based projection system

MEMS transducers:







optical signal → Signal transduction unit → Actuating element → mechanical movement

packaging

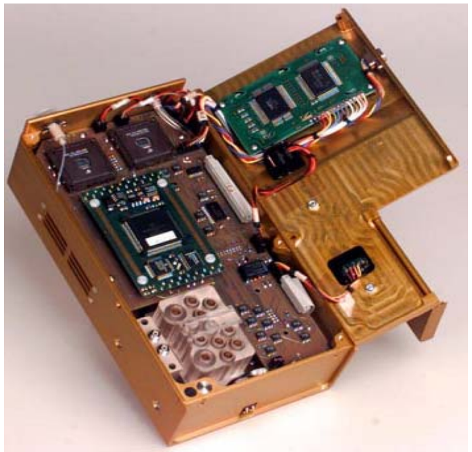
Power supply

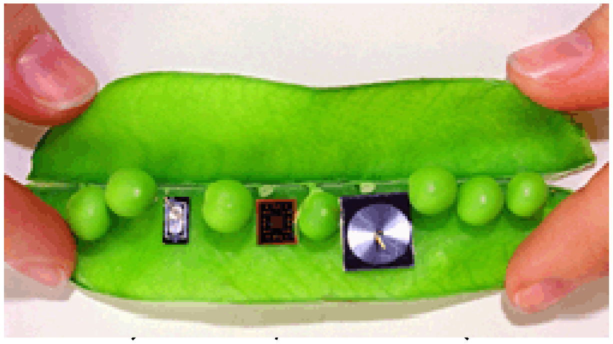
Digital light processor of Taxes Instrument (TI)

http://www.dlp.com/dlp_technology/default.asp

Typical MEMS/Microsystems- µChemLab

Microsystems:





µChemLab™ by Sandia National Laboratory

Function:

Liquid-phase system: discriminate proteins to detect and identify biotoxins, viruses, and bacterial agents.

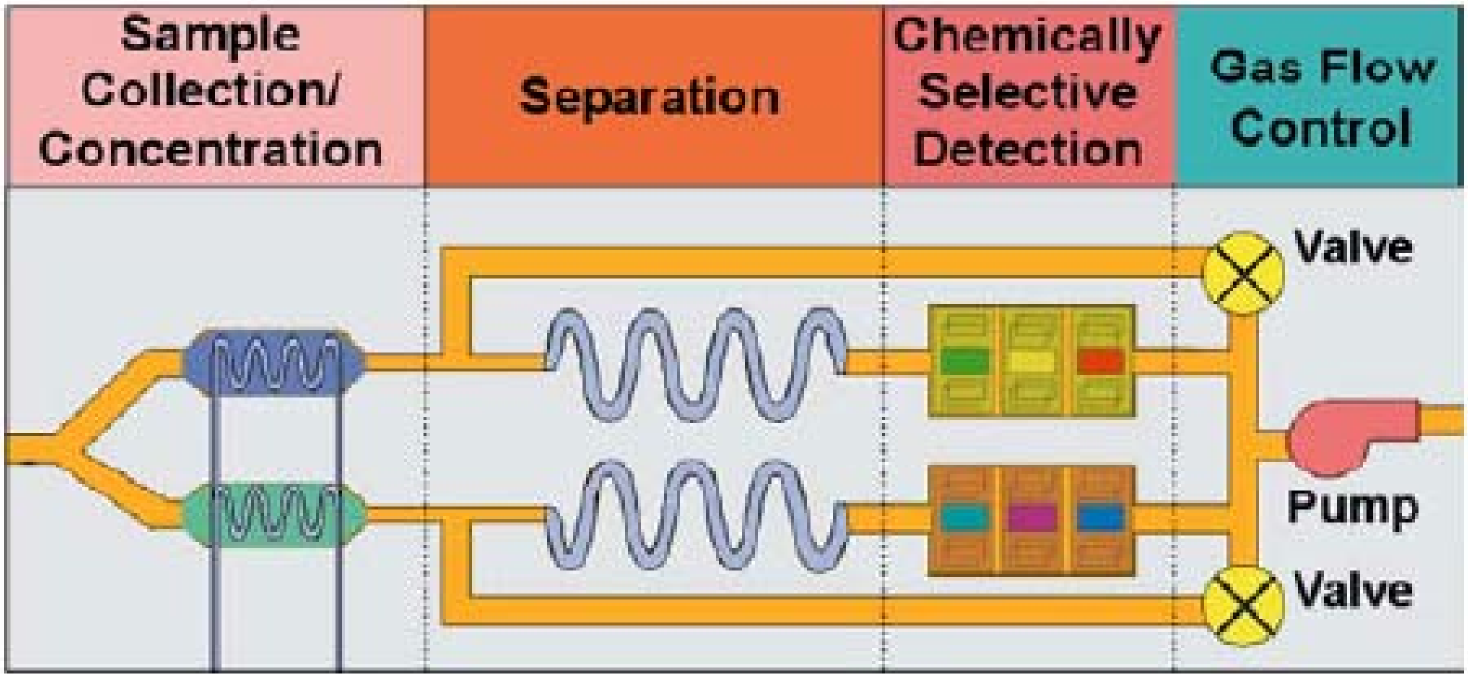
Gas-phase system: detection of chemical warfare agents and a selection of toxic industrial chemicals, explosives, and organic solvents.

Components:

The breadboard provides power conditioning and switching, thermal monitoring and control of gas analysis components, analog-to-digital data conversion, fan, pump, and valve control, and operational timing and sequencing. The Gas Module is made up of **microfabricated** Preconcentrators, Gas Chromatograph separation columns, and Surface Acoustic Wave chemical detectors.

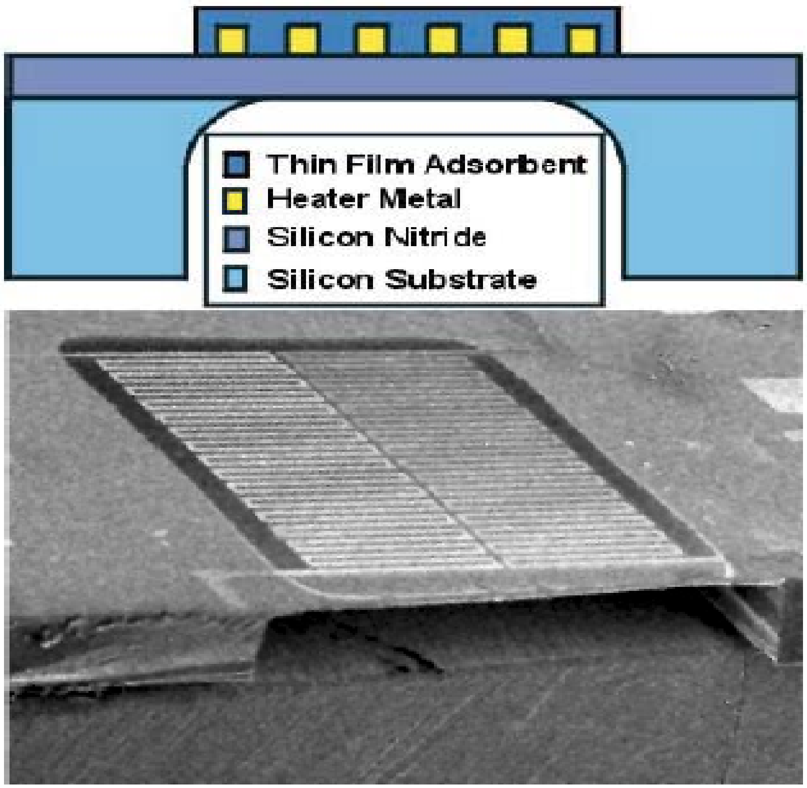
Detail: http://www.sandia.gov/news-center/news-releases/2003/mat-chem/chempartners.html

Examples of MEMS and Microsystems- μChemLab

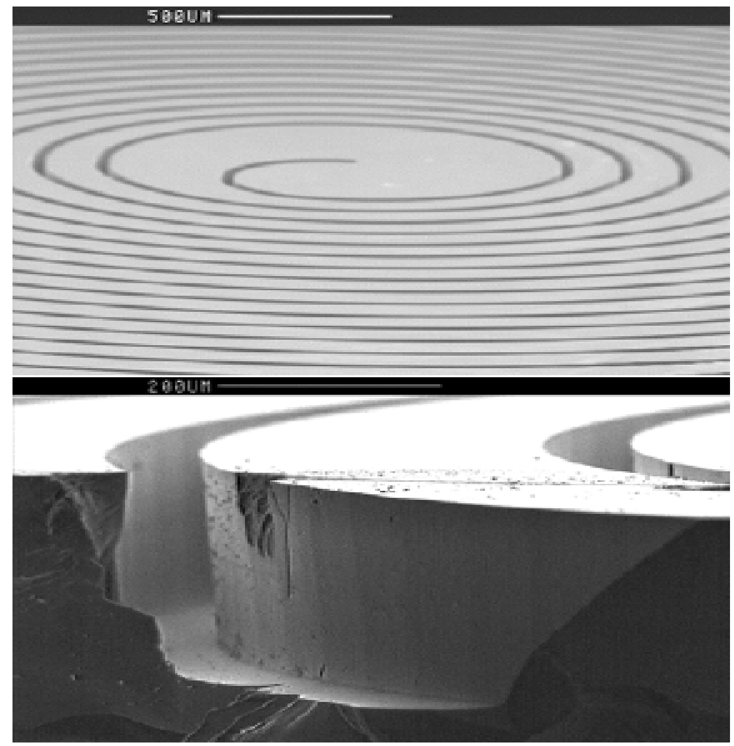


Sketch of gas-phase system

Sample collection and concentration units in μChemLab

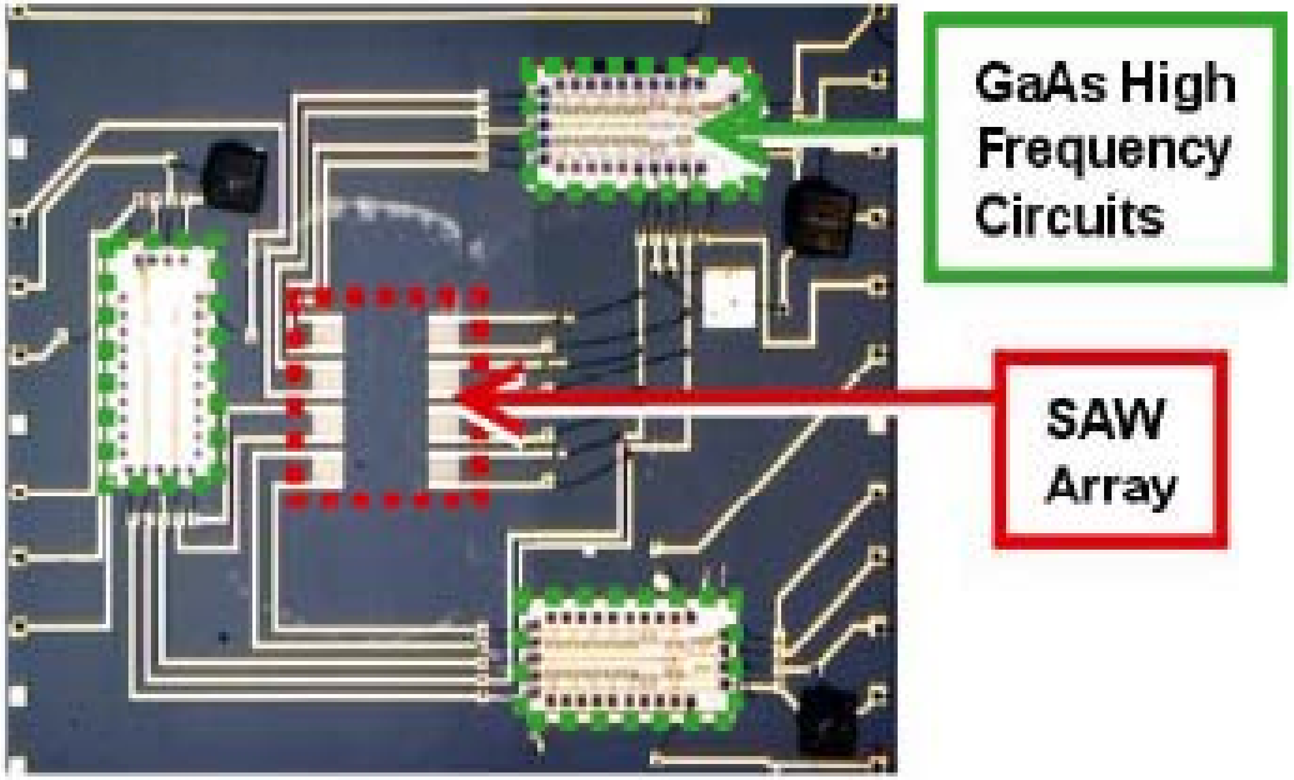


Micromachined Collection and pre concentration unit



Micromachined Gas chromatography

SAW sensor in μChemLab



Array of Surface Acoustic Wave (SAW) detector

Examples of MEMS and Microsystems- bioMEMS

other MEMS applications:

sensors

- potential, pressure, force, pH, chemistry

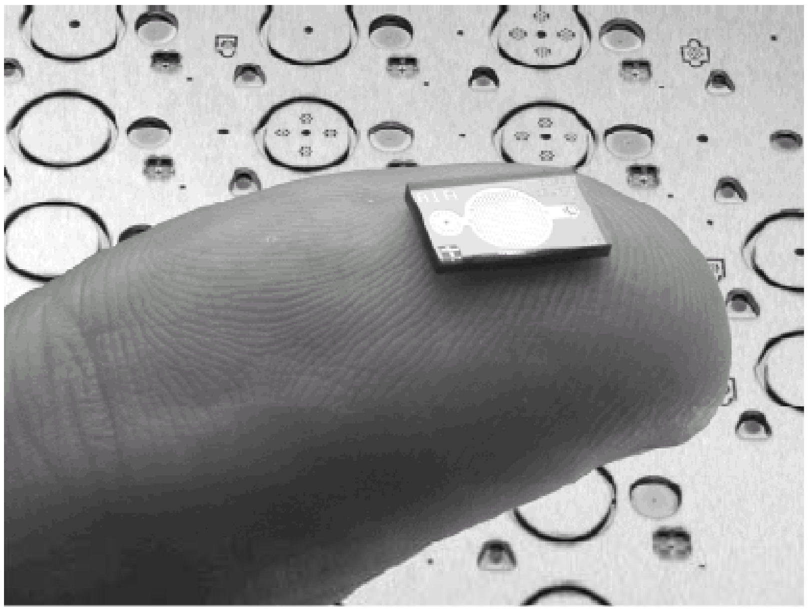
actuators

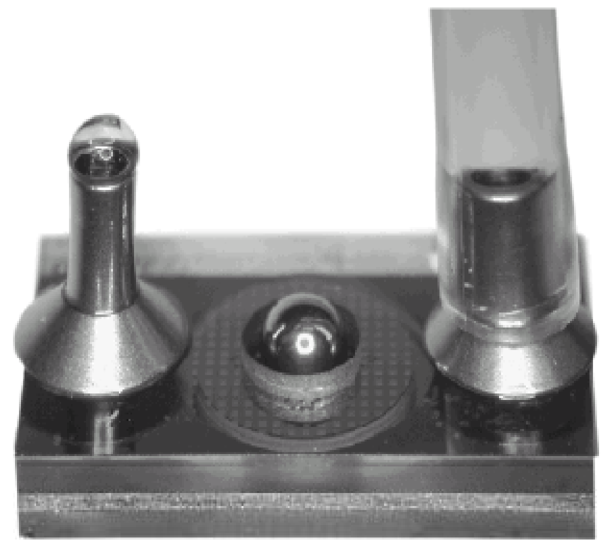
- pumps, valves, probes, grippers, ...

systems

- Integrated microfluidic platforms
- Lab-on-a-chip systems

Examples of MEMS and Microsystems- Insulin MEMS pump

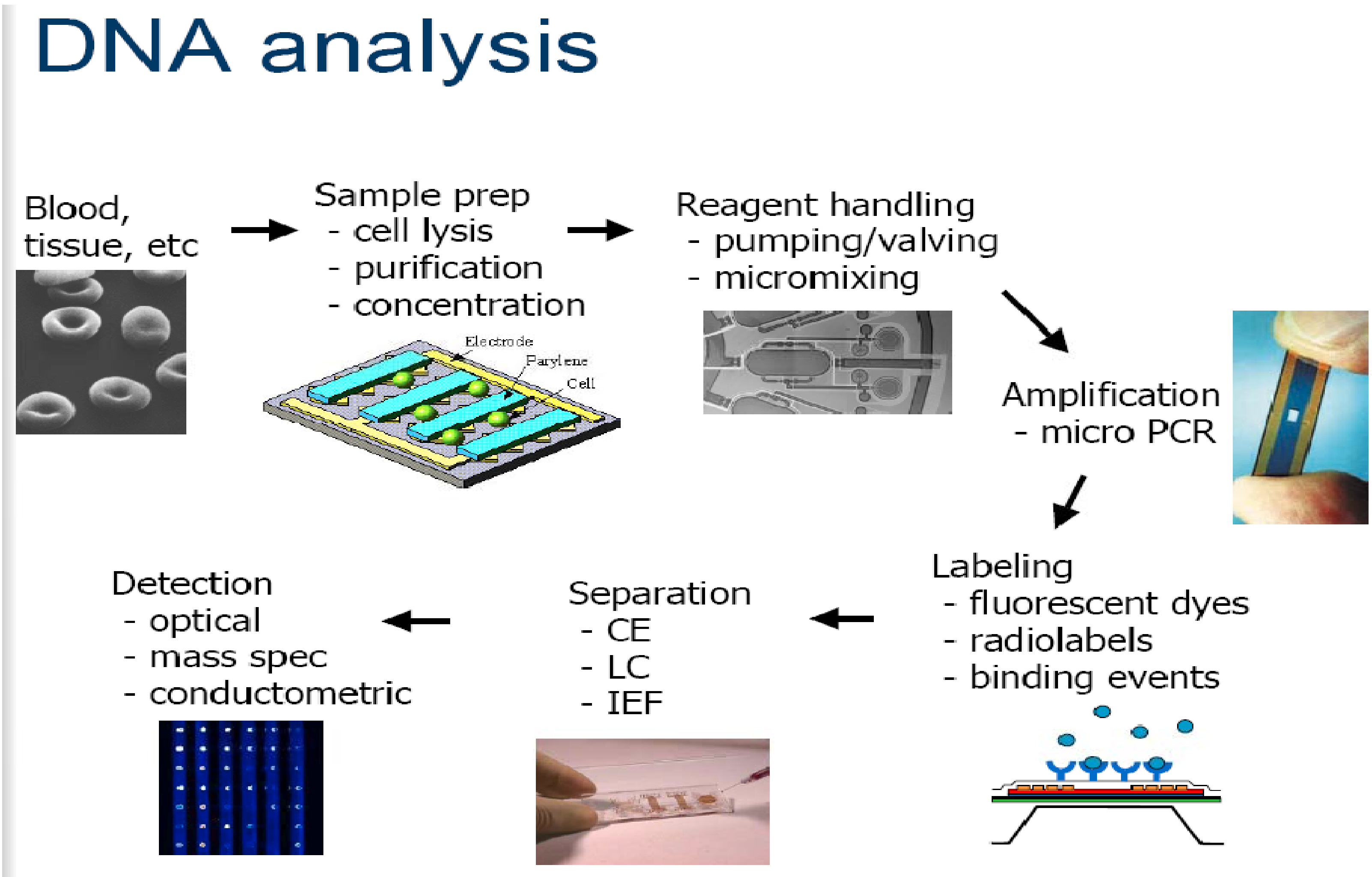




Pump size = 6mm x 10mm

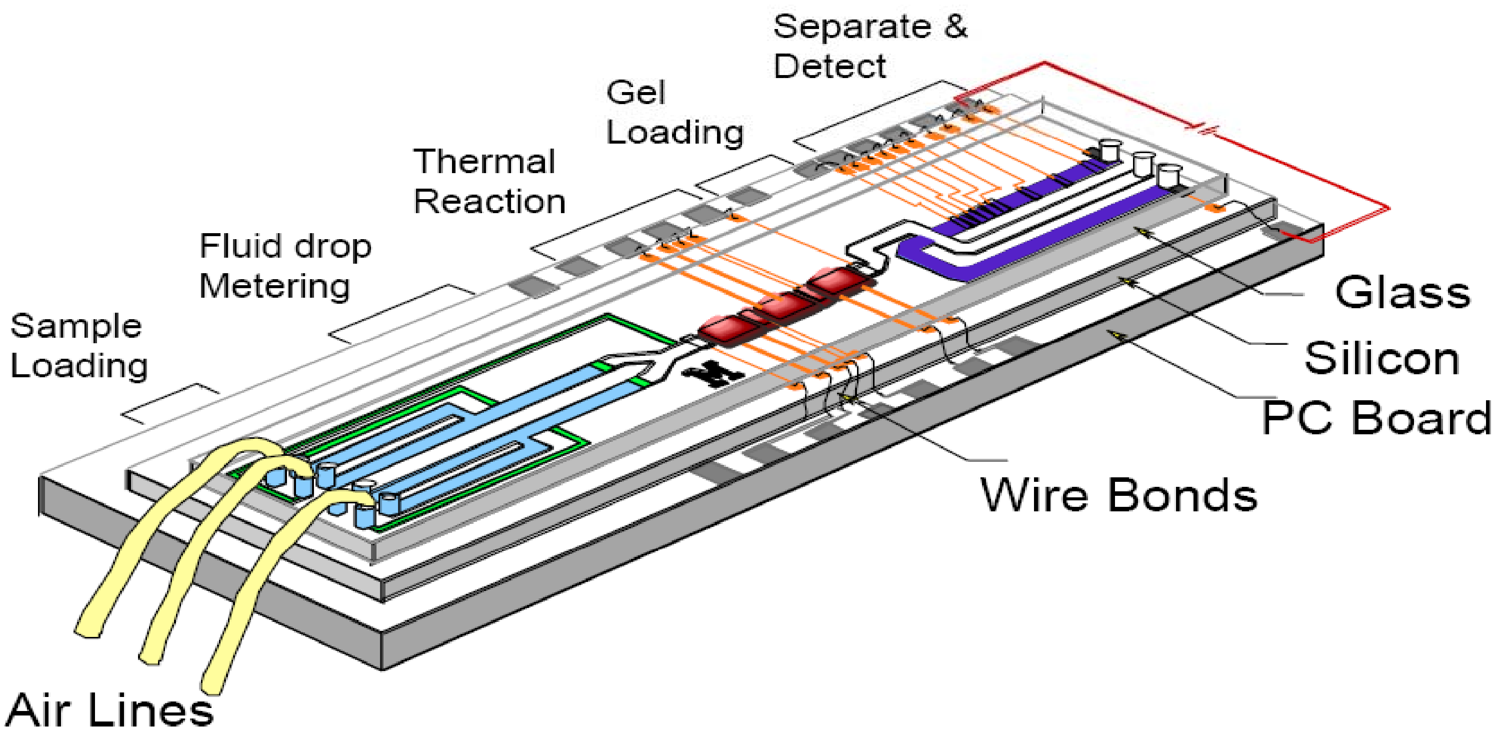
Diabetes is a medical condition where the body does not manufacture its own insulin. Insulin is used to metabolise sugar and, if it is not available, the person suffering from diabetes will eventually be poisoned by the build-up of sugar. It is important to maintain blood sugar levels within a safe range as high levels of blood sugar have long-term complications such as kidney damage and eye damage. These are not however, normally dangerous in the short-term. Very low levels of blood sugar (hypoglaecemia) are potentially very dangerous in the short-term. They result in a shortage of sugar to the brain which causes confusion and ultimately a diabetic coma and death. In such circumstances, it is important for the diabetic to eat something to increase their blood sugar level.

Examples of Microsystems (Lab-on-a Chip)- DNA analysis



Examples of Microsystems (Lab-on-a Chip)- DNA analysis

Integrated DNA Analysis



Drawing courtesy of C. Mastrangelo, U. Michigan

Microsystems- DNA detector

- Adsorption of small molecules induces surface stress through electrostatic interactions and steric hindrance, which can bend a cantilever
- This study applied the above principle to DNA fragments, which should only induce significant surface stress if the fragment on the cantilever is a precise match.

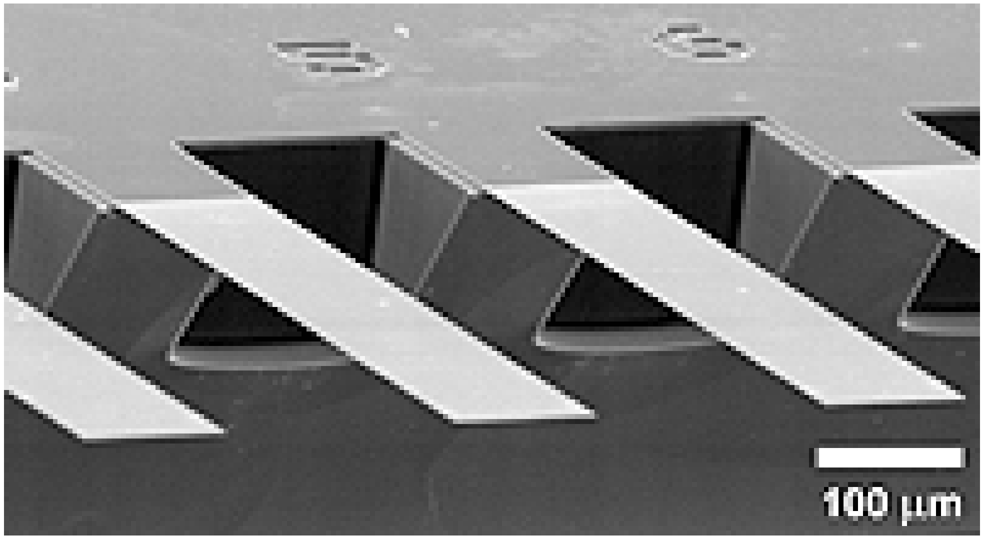
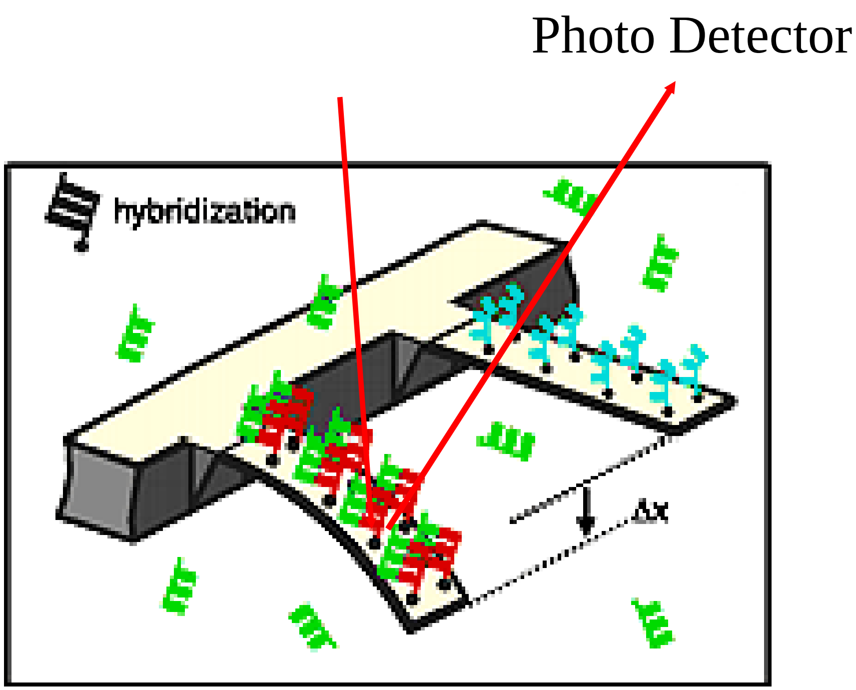
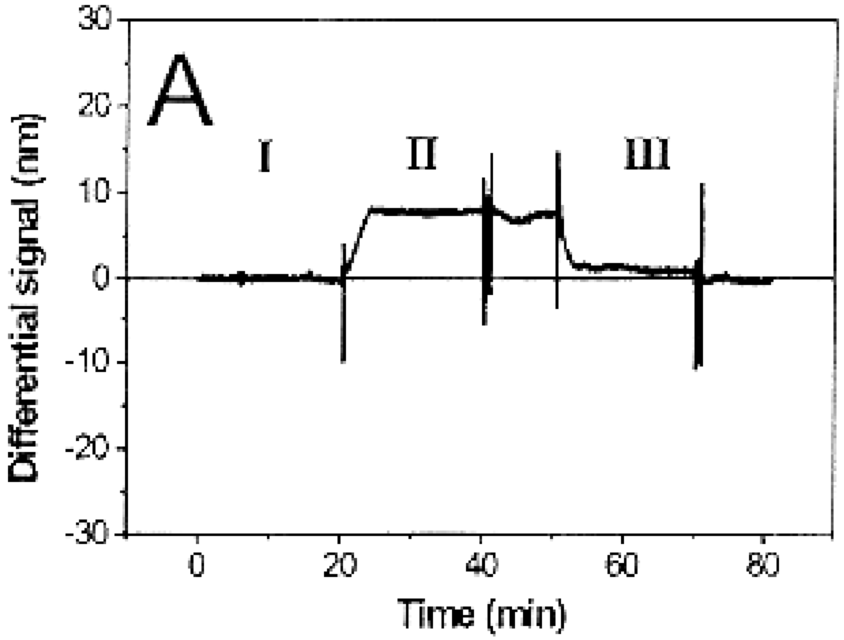


Fig. 1. Scanning electron micrograph of a section of a microfabricated silicon cantilever array (eight cantilevers, each 1 µm thick, 500 µm long, and 100 µm wide, with a pitch of 250 µm, spring constant 0.02 N m^{-1} ; Micro- and Nanomechanics Group, IBM Zurich Research Laboratory, Switzerland).

Prof Jiang Zhe U. of Akron

Examples of MEMS and Microsystems- DNA detector





Books and references

<u>MEMS books:</u>

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3. **Marc Madou, *Fundamentals of Microfabrication*, 2nd Edition, CRC, 2002**
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10. Gabriel Rebeiz, *RF MEMS: Theory, Design, and Technology*, Wiley, 2003
11. Nam-Trung Nguyen and Steve Wereley, *Fundamentals and Applications of Microfluidics*, Artech House, 2002
12. Stephen Campbell, *The Science & Engineering of Microelectronic Fabrication*, 2nd Edition, Oxford, 2001
13. James Gere, *Mechanics of Materials*, 5th Edition, Brooks/Cole, 2001

MEMS website and Journals, conferences

Website: http://www.memsnet.org/

Journals: Journal of Microelectromechanical System (J.MEMS) (IEEE/ASME)
Sensors and Actuators (ELSEVIER)
Journal of Micromechanics & Microengineering
And more

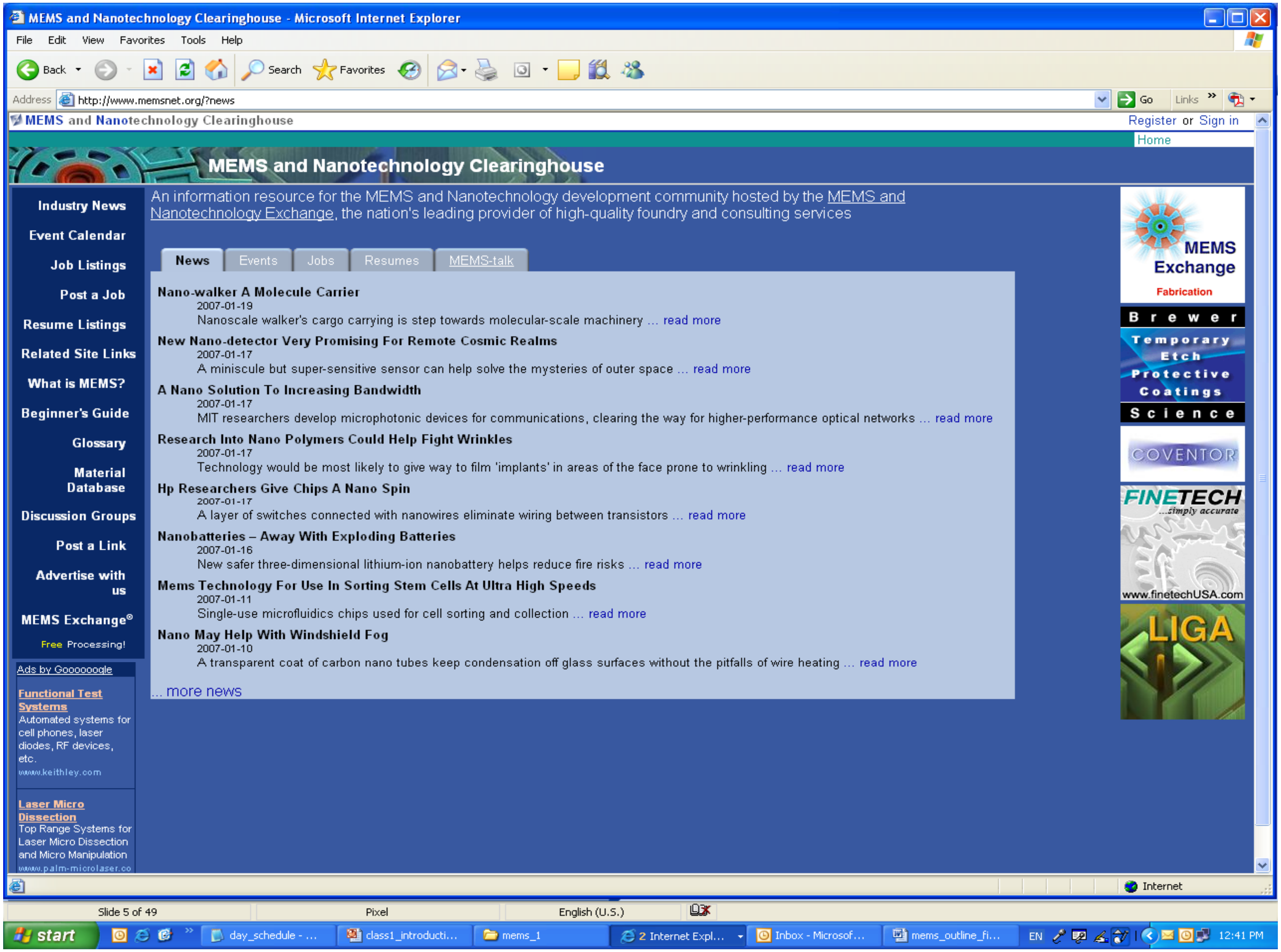
MEMS companies: http://www.memsnet.org/links/ (hundreds of companies)

Conferences:

1. Hilton Head , Solid-State Sensors, Actuator, and Microsystem Workshop ,Transducer Research Foundation
2. International MEMS conference (IEEE)
3. Micro Total Analysis System (uTAS)

And more at http://home.earthlink.net/~trimmerw/mems/Conferences.html

Website: http://www.memsnet.org/



Nanoelectromechanical Systems (NEMS)

NEMS: Definitions

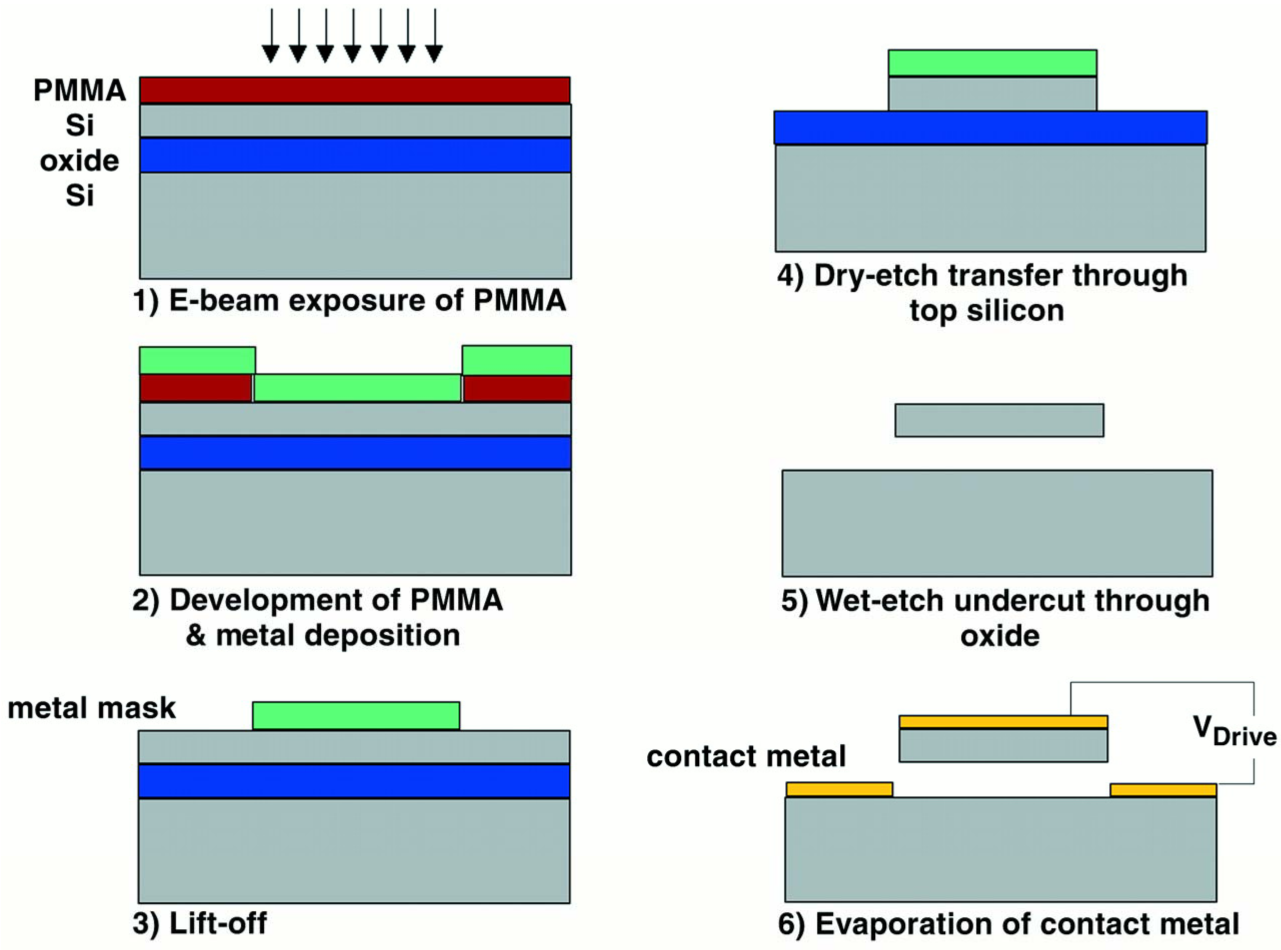
NEMS or **nanoelectromechanical systems** are similar to MEMS but smaller. They hold promise to improve abilities to measure small displacements and forces at a molecular scale.

There are two approaches most researchers accept as standard paths to NEMS. The top-down approach can be summarized as "a set of tools designed to build a smaller set of tools". For example, a millimeter sized factory that builds micrometer sized factories which in turn can build nanometer sized devices. The other approach is the bottom-up approach, and can be thought of as putting together single atoms or molecules until a desired level of complexity and functionality has been achieved in a device. Such an approach may utilize molecular self-assembly or mimic molecular biology systems.

A combination of these approaches may also be used, in which nanoscale molecules are integrated into a top-down framework.

From Wiki

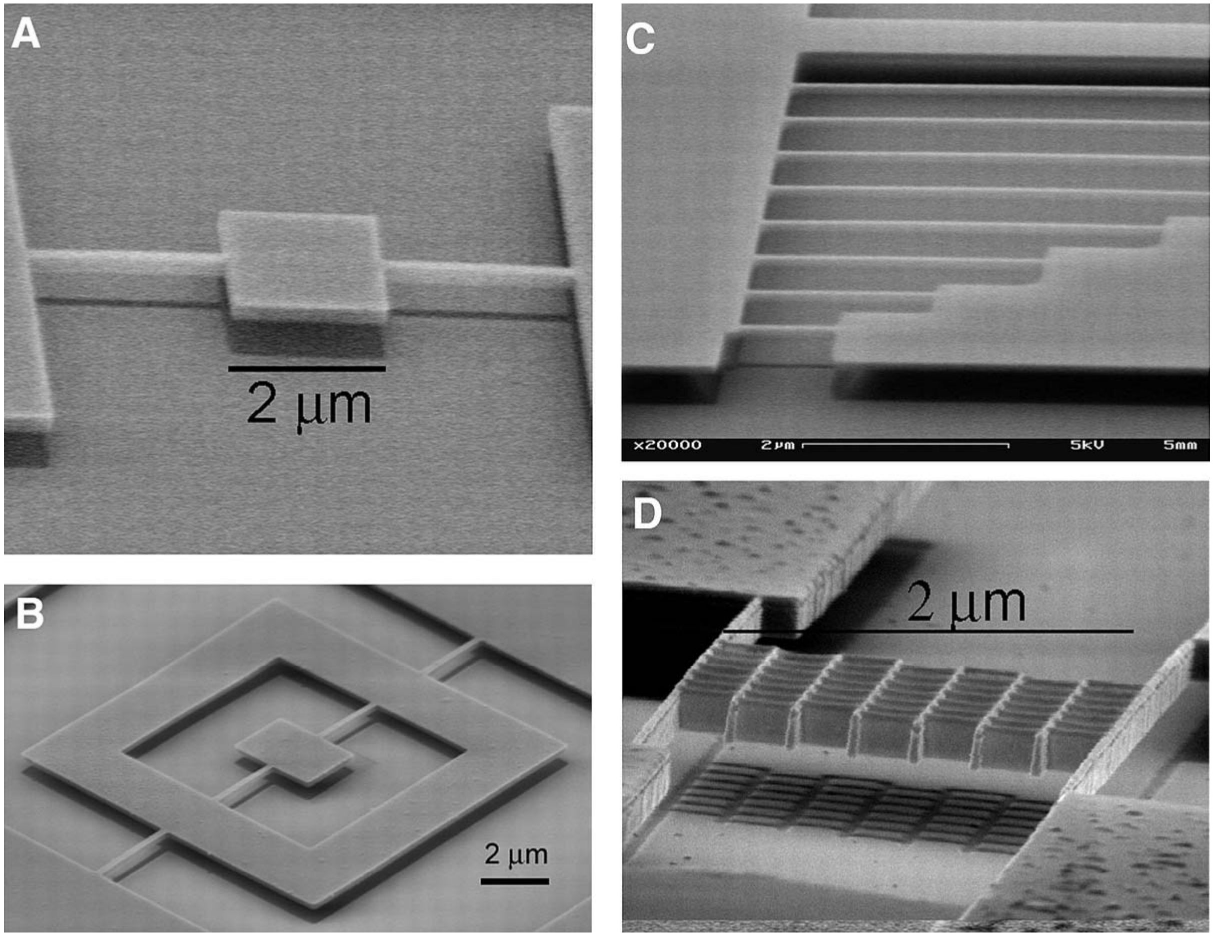
NEMS Fabrication Process



Schematic of surface micromachining approach used to nanofabricate NEMS devices. The pattern shapes are created by a scanning electron beam (E-beam) exposing a polymeric polymethylmethacrylate (PMMA) resist. The motion may be actuated by applying a voltage between the electron on the moving element and the electrode on the substrate

Science **2000**, *290*, 1532

NEMS and E-beam Lithography

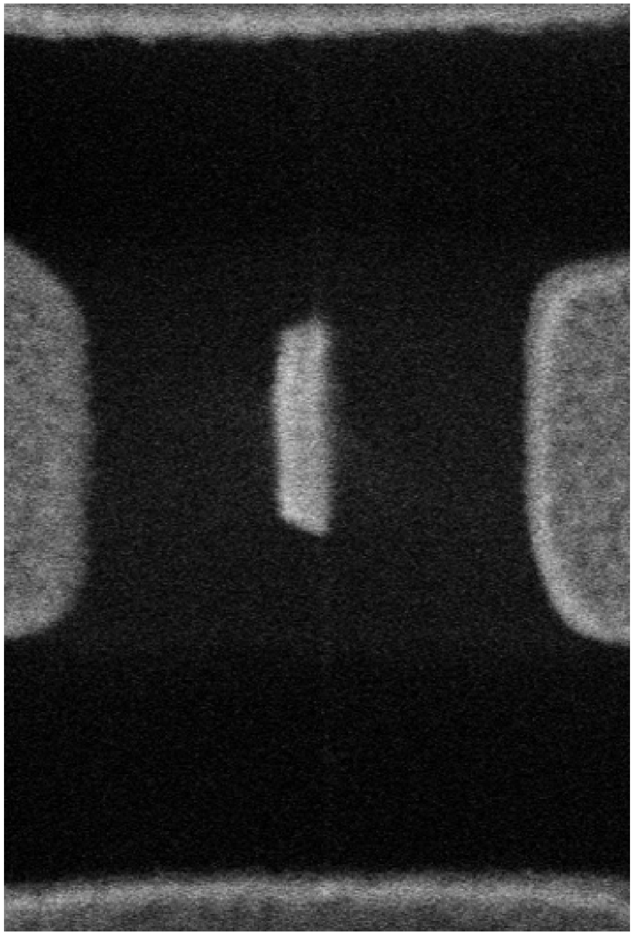


Electron micrograph of NEMS objects fabricated in single-crystal silicon by using electron beam lithography and surface micromachining. (**A**) A torsional oscillator from (15), (**B**) a compound torsional oscillator, (**C**) a series of silicon nanowires from (16), and (**D**) an oscillating silicon mesh mirror

Science **2000**, *290*, 1532

Carbon Nanotube Nanomotor

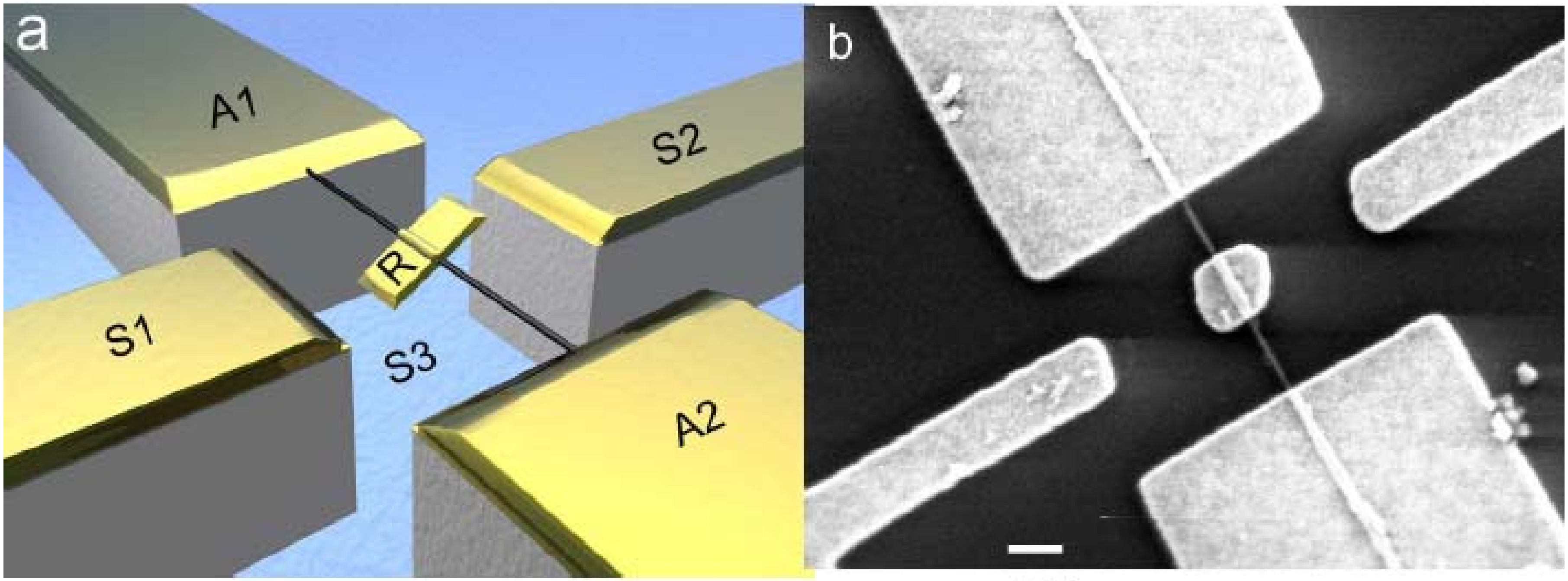
Rotational bearings based upon multiwall carbon nanotubes. By attaching a gold plate (with dimensions of order 100nm) to the outer shell of a suspended multiwall carbon nanotube, they are able to electrostatically rotate the outer shell relative to the inner core. These bearings are very robust; Devices have been oscillated thousands of times with no indication of wear. The work was done in situ in an SEM. These nanoelectromechanical systems (NEMS) are the next step in miniaturization that may find their way into commercial aspects in the future.



Nanomotor constructed at UC Berkeley. The motor is about 500nm across: 300 times smaller than the diameter of a human hair

From Wiki

Carbon Nanotube Nanomotor



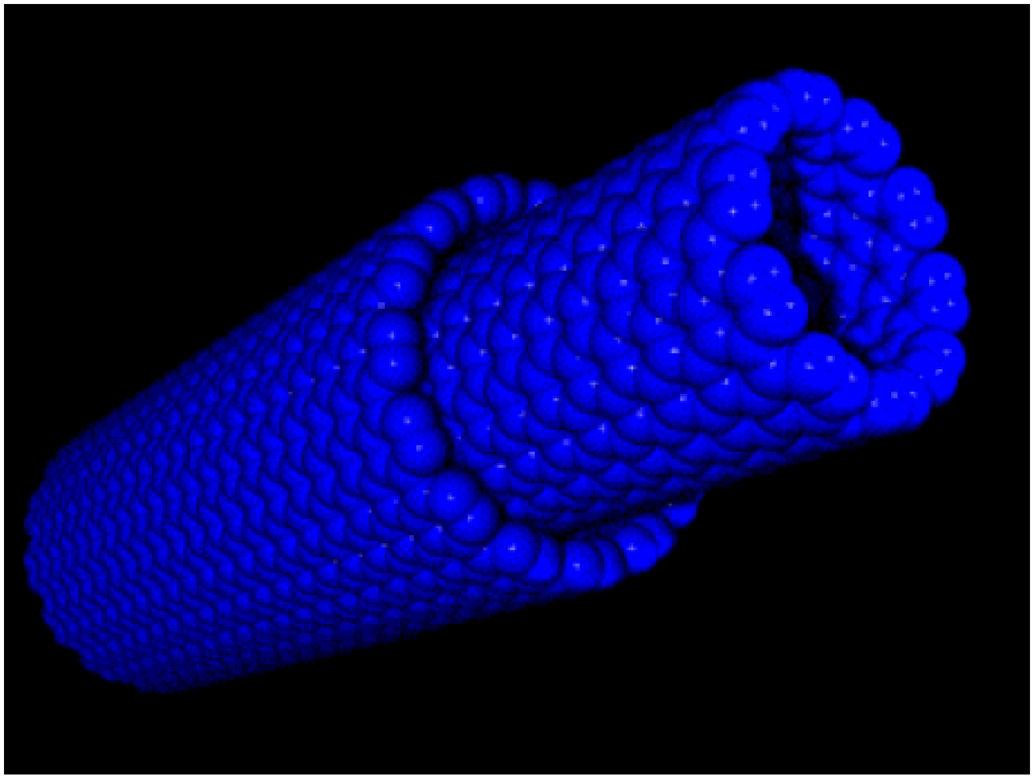
200nm

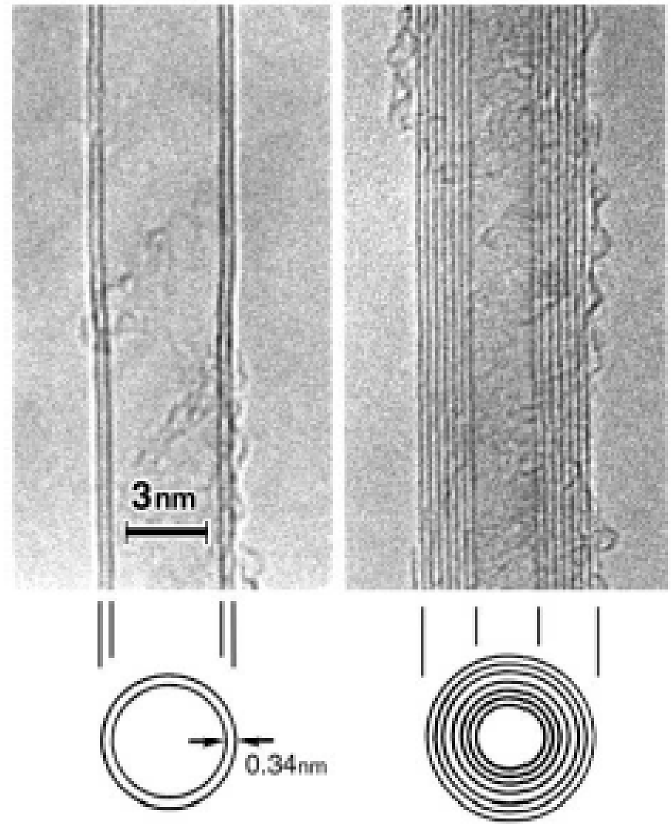
a) Schematic motor layout. R: nanotube-suspended metal plate rotor
A1, A2: anchors; S1,S2,S3: stators

b) SEM image of completed nanomotor

(Fennimore, Yuzvinsky, Zettl et al, *Nature* 2003)

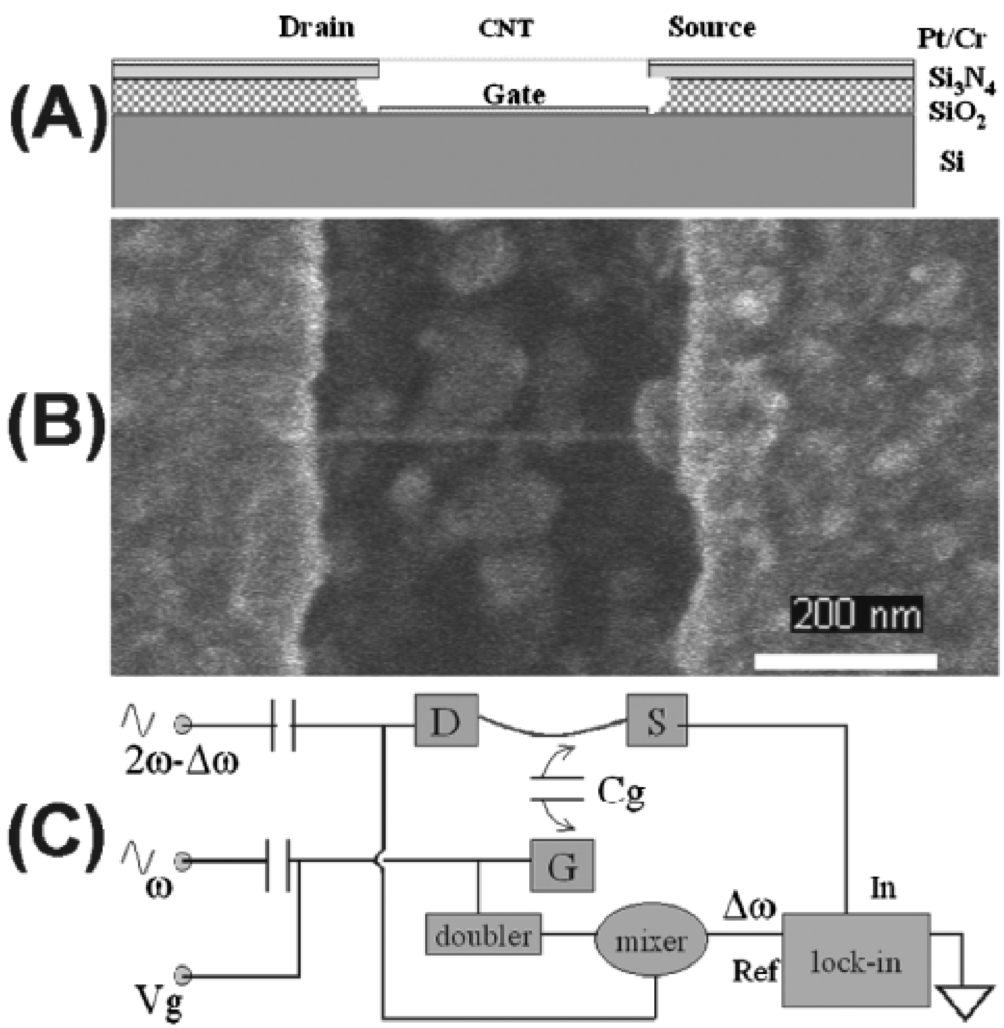
Nanotube Rotational Bearing

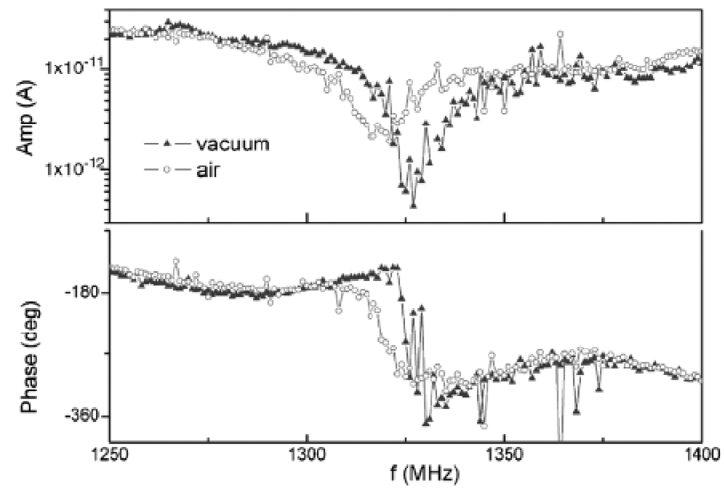




SWNT MWNT

Ultrahigh Frequency Nanotube Resonators



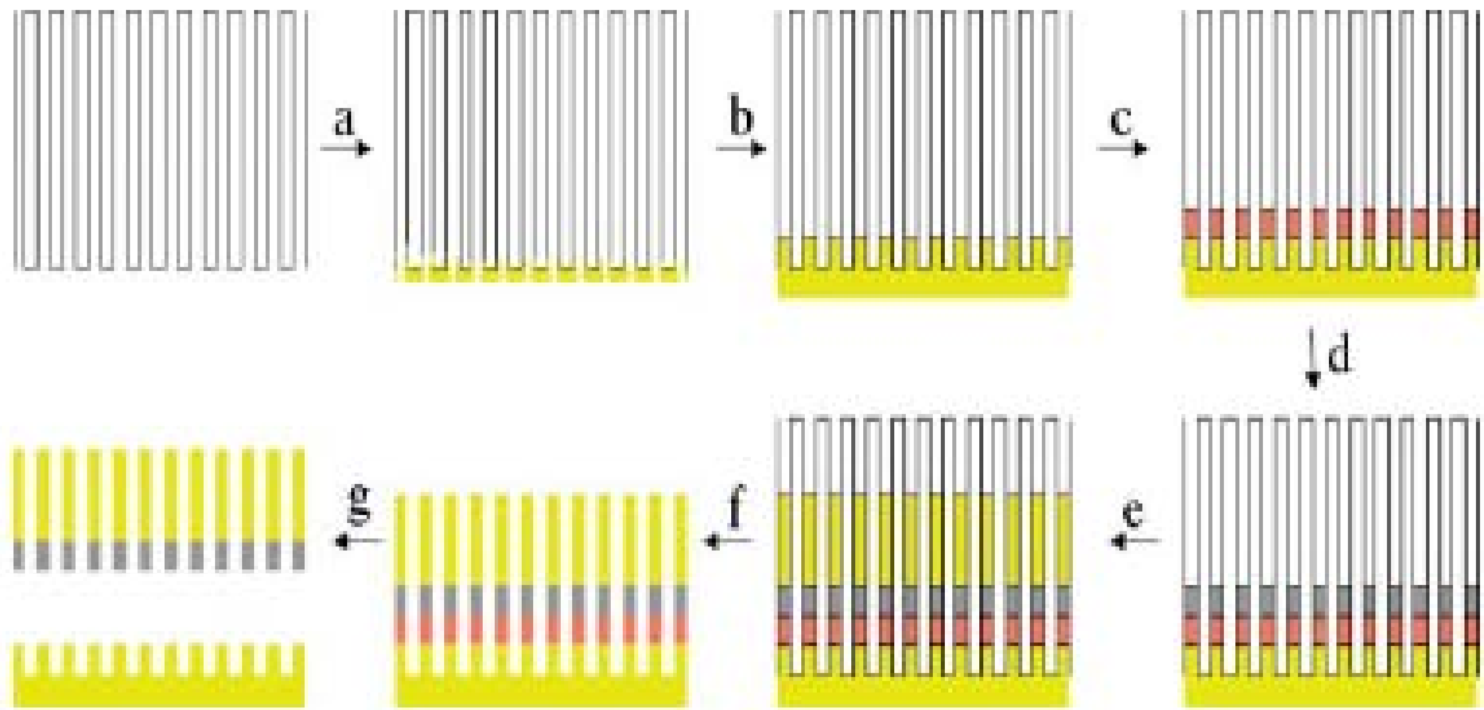


Amplitude (in logarithmic scale) and phase of the electrical current in a vacuum 106 Torr (triangles) and in air (circles) for a nanobridge resonator made from coating a bare suspended CNT device with 2.5 nm indium. The data were taken at *Vg*0, *Vg*112mV, and *Vd* 46 mV by the 1*!* method.

PRL **97,** 087203 (2006)

manufacturing center at UML

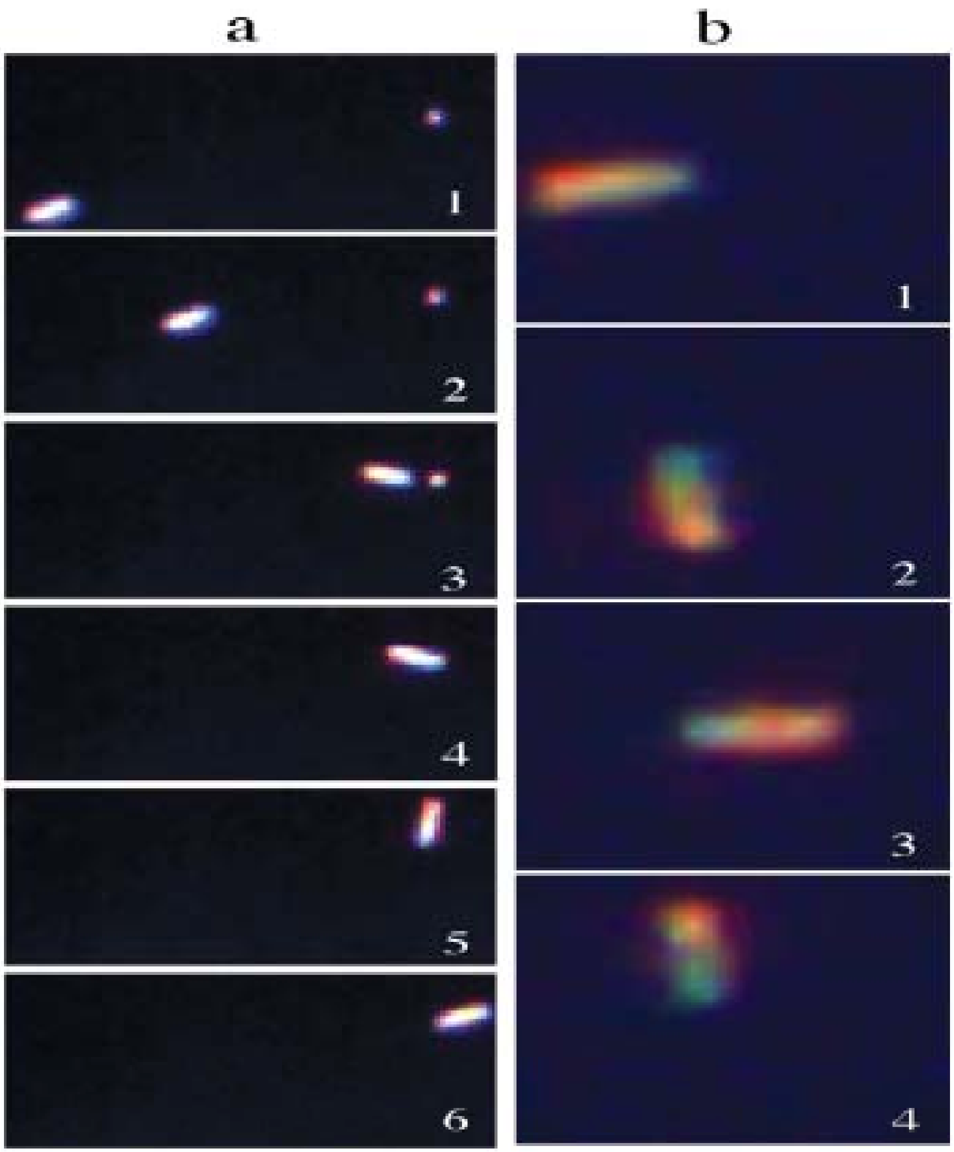
Example I: Self-Propelled Nanorotors



Schematic of nanobarcode synthesis. (a) Gold sputtering onto an alumina membrane. (b) Electrodeposition of gold plugs. (c) Electrodeposition of a sacrificial layer of copper. (d) Electrodeposition of nickel segment. (e) Electrodeposition of gold segment. (f) Selective dissolution of alumina. (g) Selective dissolution of copper.

Chem. Commun., **2005**, 441–443

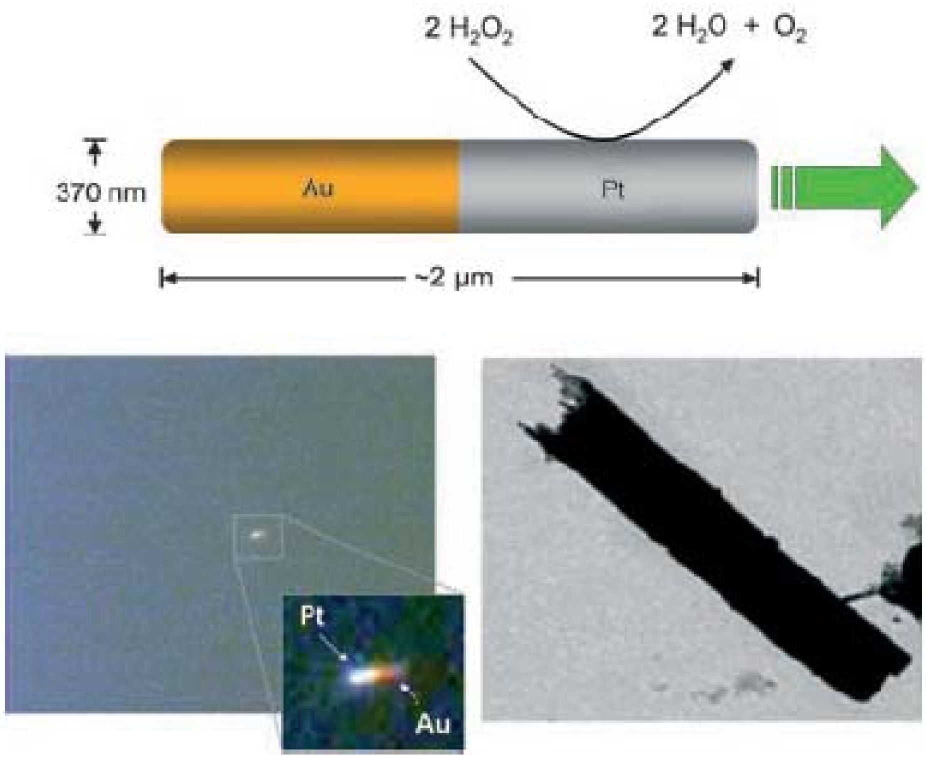
Self-Propelled Nanorotors



(a) Optical microscope snapshots of a nanorod rotating counterclockwise. (b) Optical microscope snapshots showing the dynamics of a suspended nanorod with a near-linear movement followed by tethering to a surface impurity that induces a circular movement.

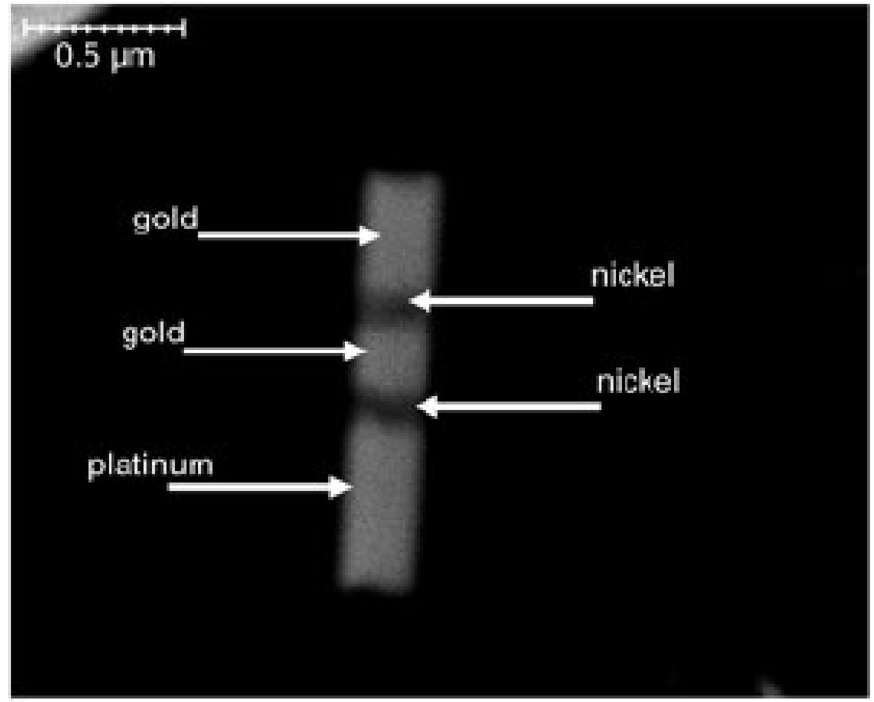
Chem. Commun., **2005**, 441–443

Example: Catalytic Nanomotors



Platinum/gold nanorods composite: Top: Schematic of a platinum/gold nanorod. Bottom left: An optical micrograph (500I) of a platinum/gold rod. Bottom right: TEM of a platinum/gold rod.

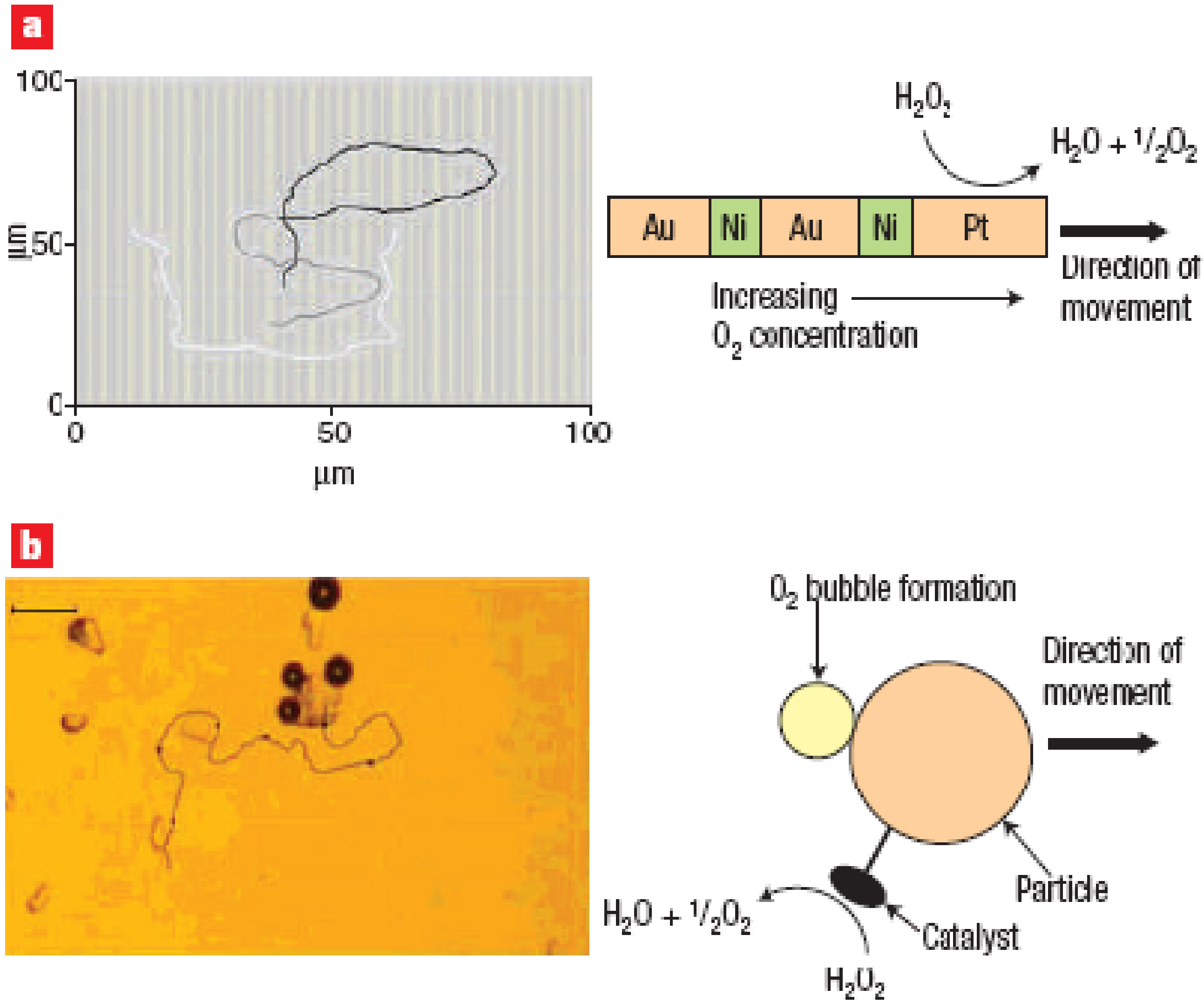
Chem. Eur. J. **2005**, *11*, 6462 – 6470



An SEM image at 35000 magnification of 1.5 mm400 nm striped metallic rod. Respective segment sizes (nm): Au, 350; Ni, 100; Au, 200; Ni, 100; Pt, 550.

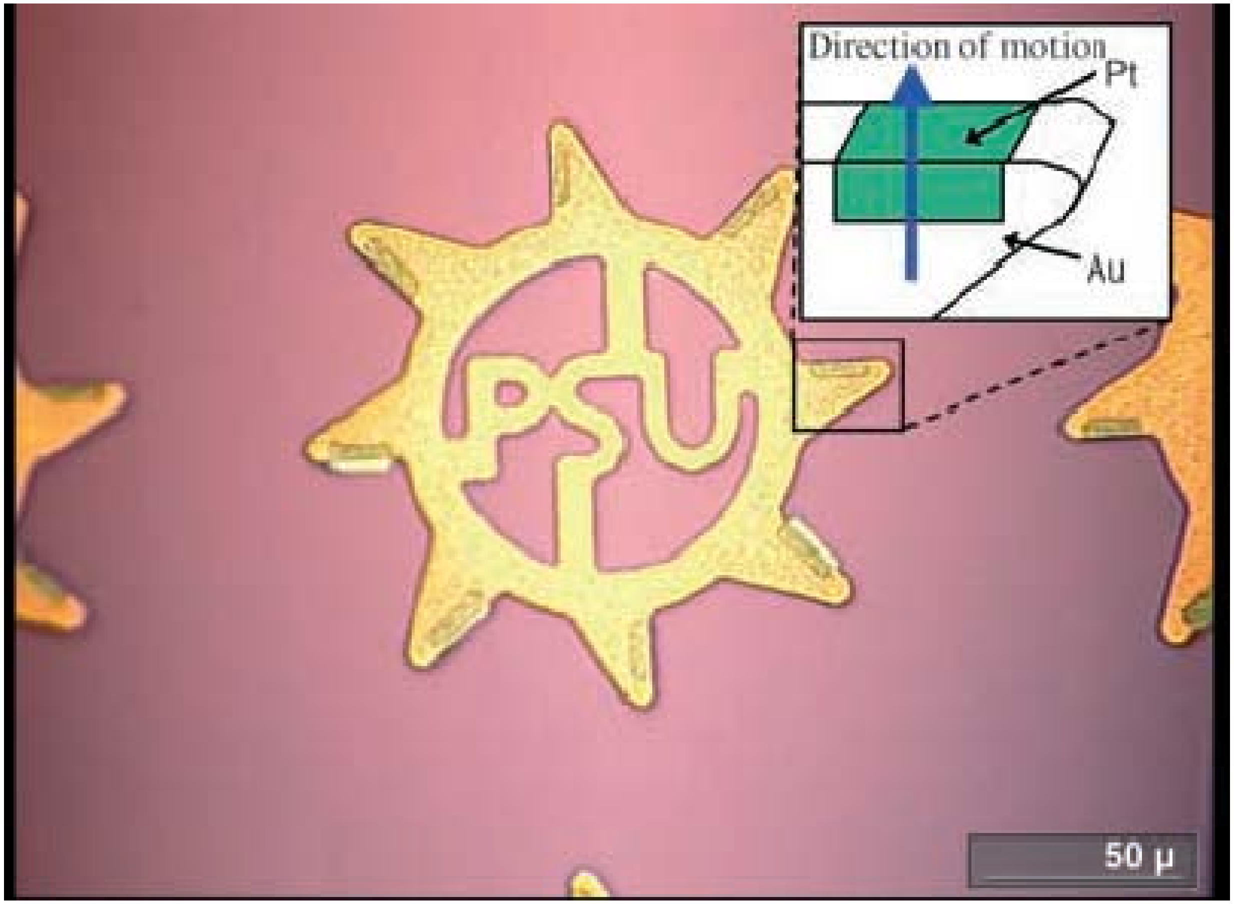
Angew. Chem. Int. Ed. **2005**, *44*, 744 –746

Catalytic Nanomotors



Browne & Feringa, Nature Nanotechnology, **2006**, *1*, 25-35

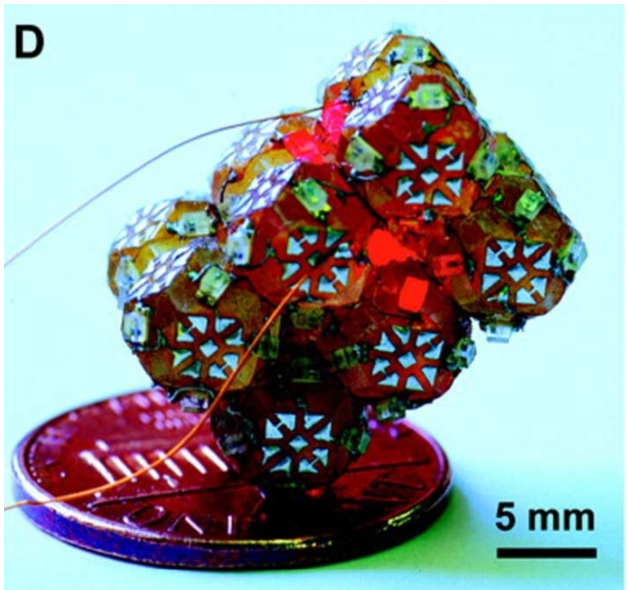
Catalytic Nanomotors

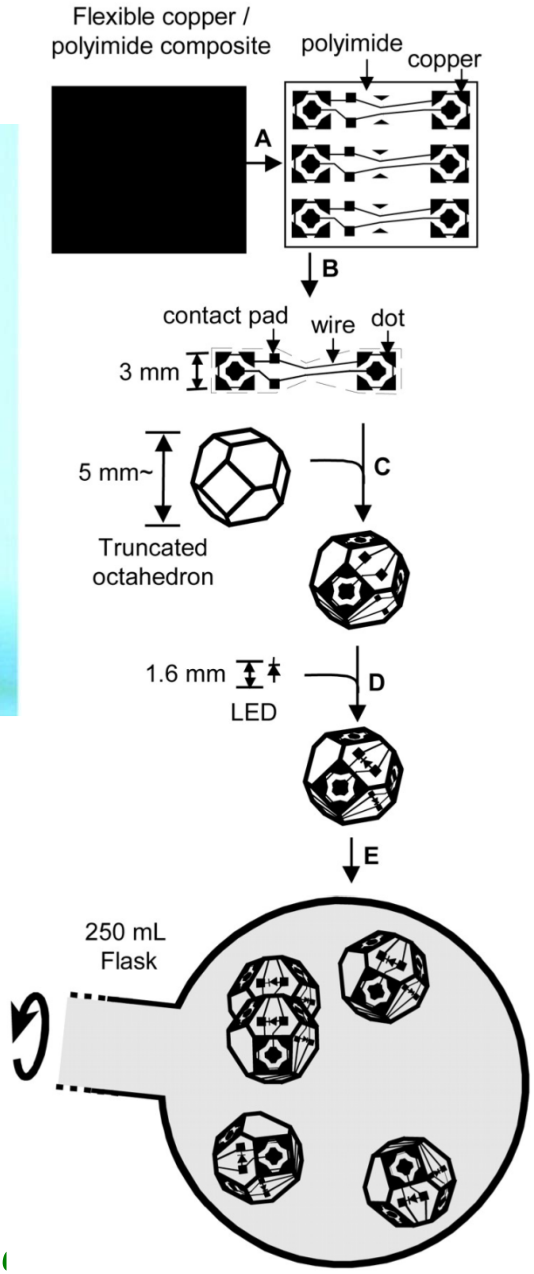


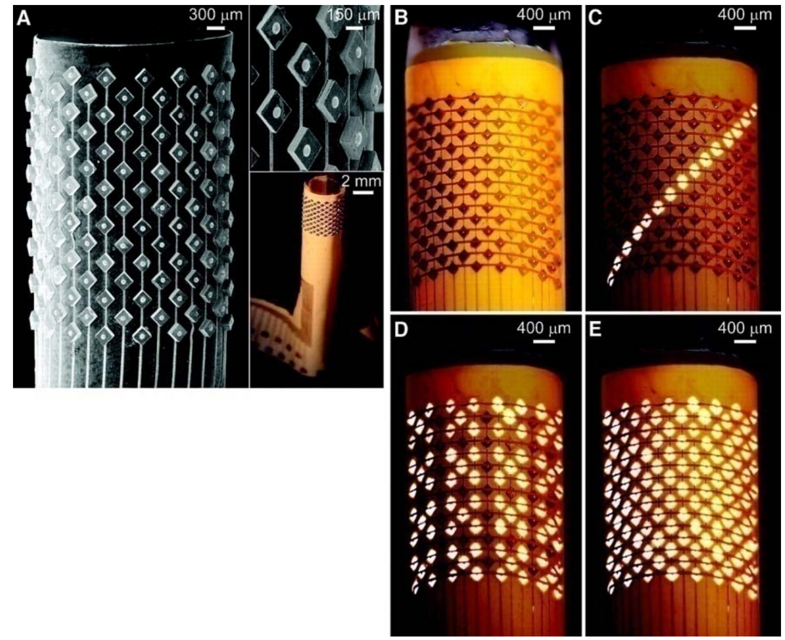
Microfabricated gold “gears” with platinum on one side of each of the teeth. The result is the counterclockwise rotation of the structure when placed in hydrogen peroxide solution

Chem. Eur. J. **2005**, *11*, 6462 – 6470

Self-Assembly of Electronic Systems







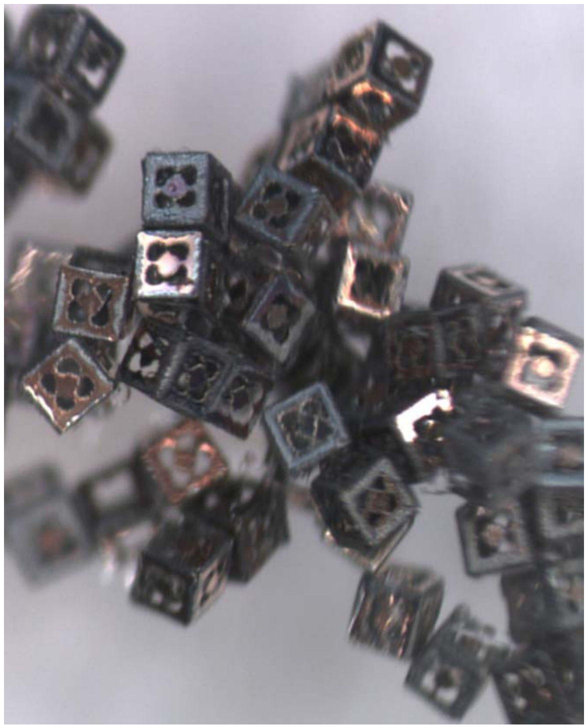
Millimeter scale

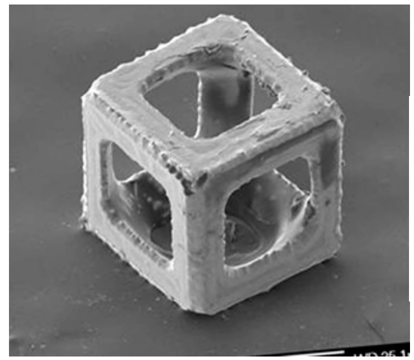
Gracias, Tien, Breen, Hsu, Whitesides.
Science 2000, *289*, 1170.

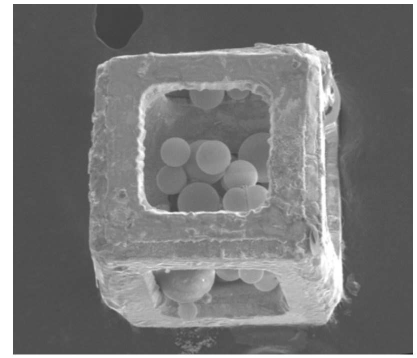
200 µm scale

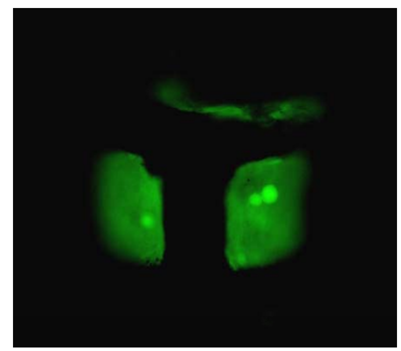
Jacobs, Tao, Schwartz, Gracias, Whitesides.
Science 2002, *296*, 323.

Self-Assembled Self-folding Micro-Containers





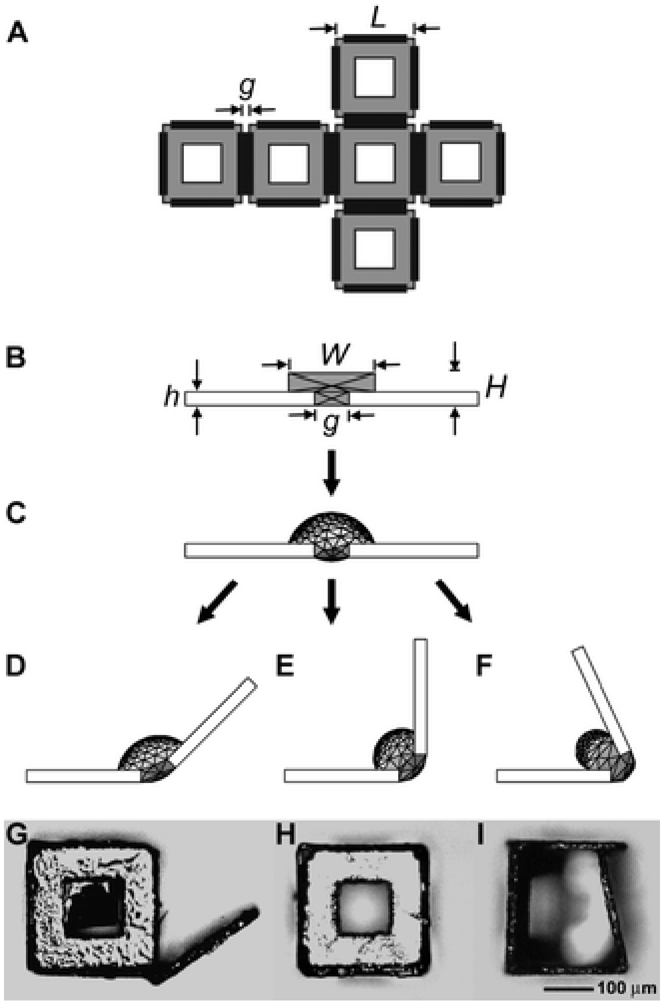


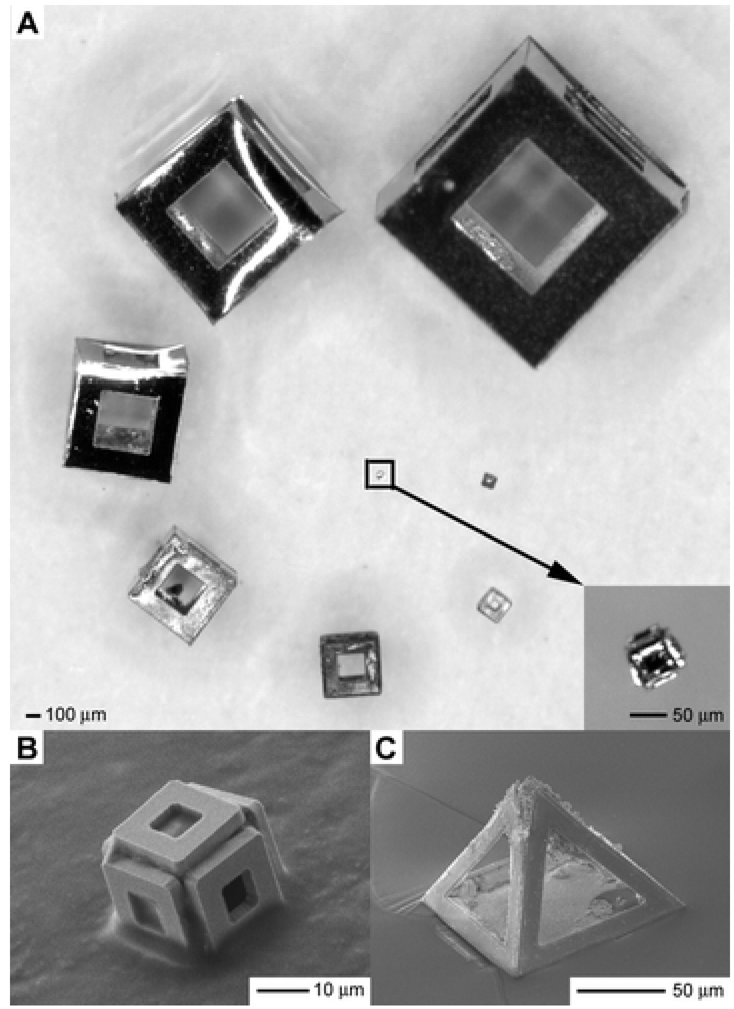


100-200 μm

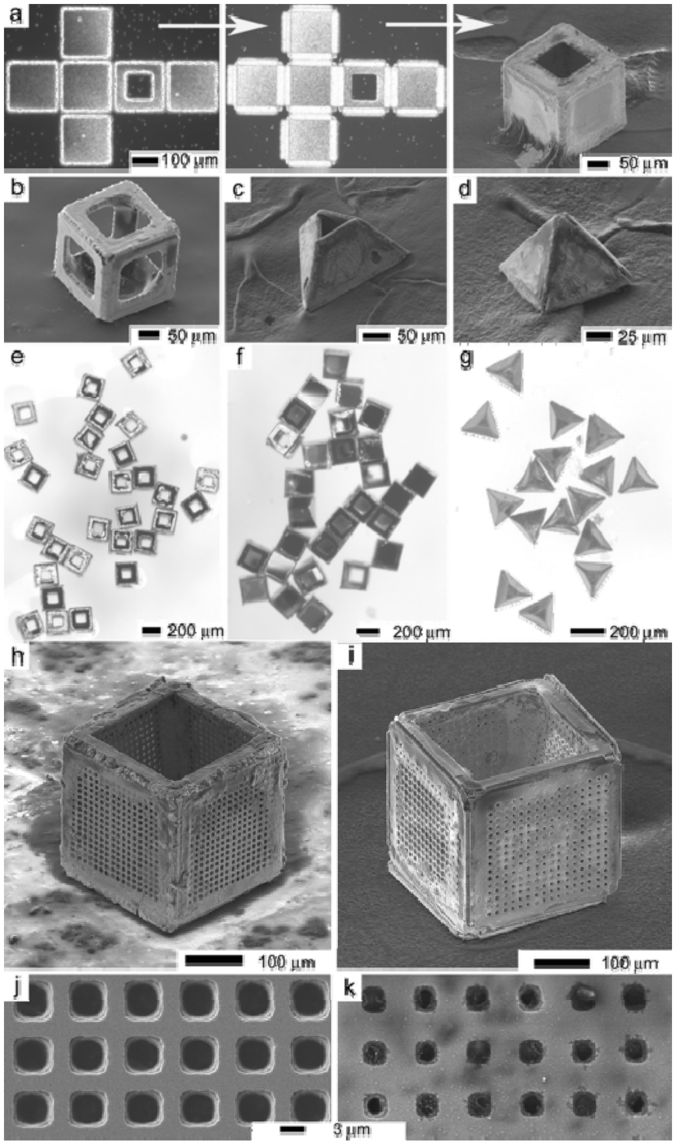
Gimi, Leong, Gu, Yang, Artemov, Bhujwalla, Gracias. *Biomedical Microdevices* 2005, *7*, 341-345.

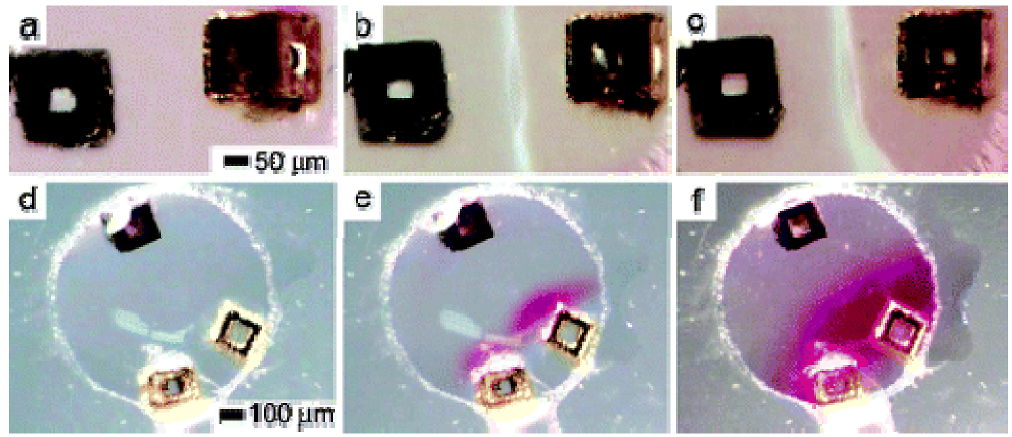
Self-Assembled Self-folding Micro-Containers





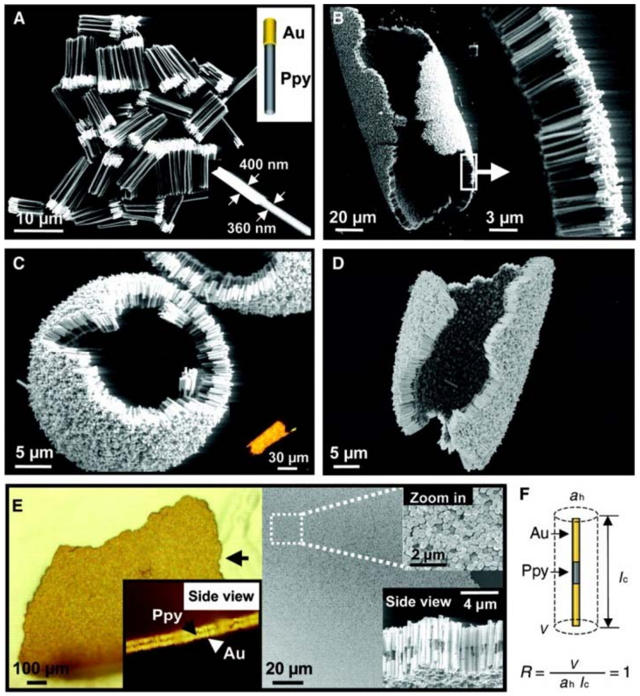
Self-Assembled Self-folding Micro-Containers

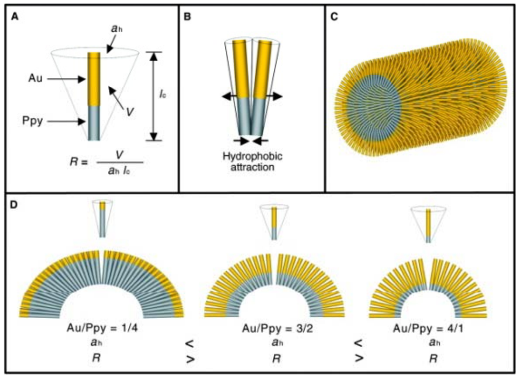




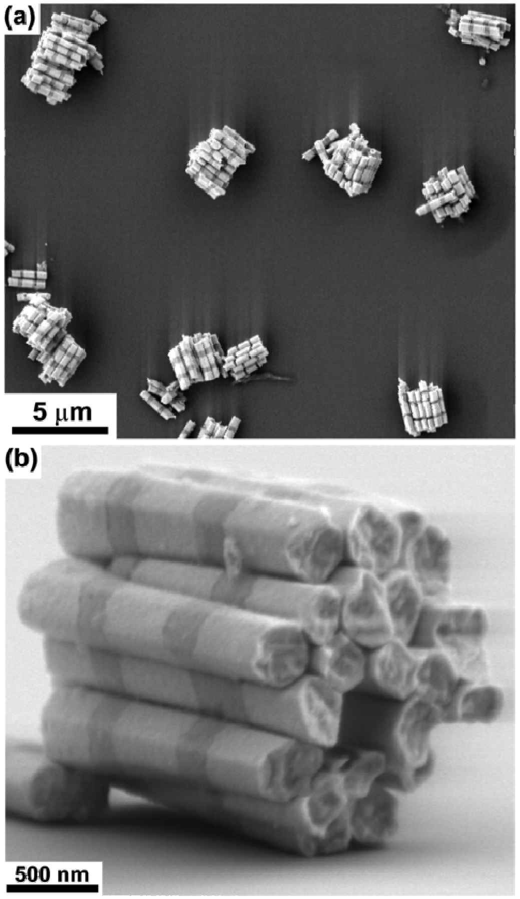
Leong, Gu, Koh, Gracias. *JACS* 2006, *128*, 11336-11337

Self-Assembly of Nanowires





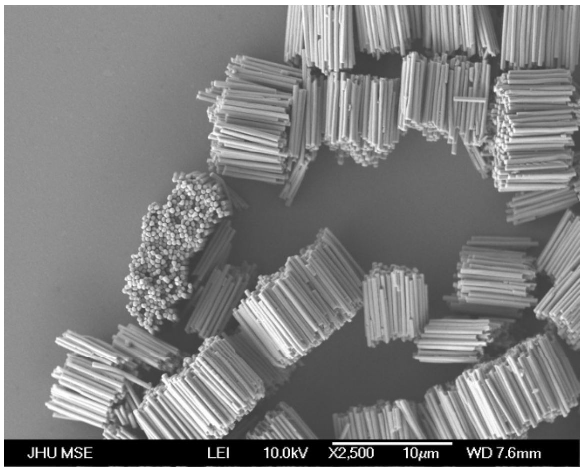
Park, Lim, Chung, Mirkin. *Science* 2004, *303*, 348



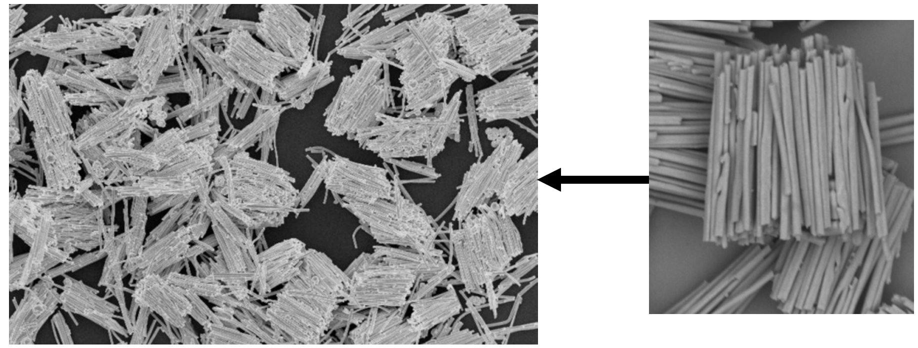
Magnetic assembly

Love, Urbach, Prentiss, Whitesides. *JACS*, 2003, *125*, 12696.

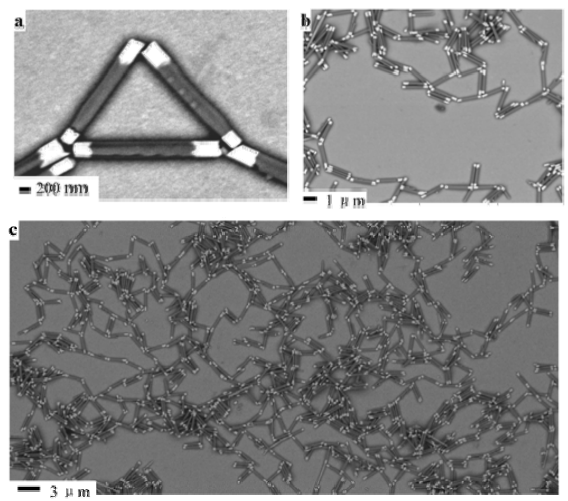
Self-Assembly of Nanowires



Large scale bundles during membrane dissolution



"Glued" 3D bundles

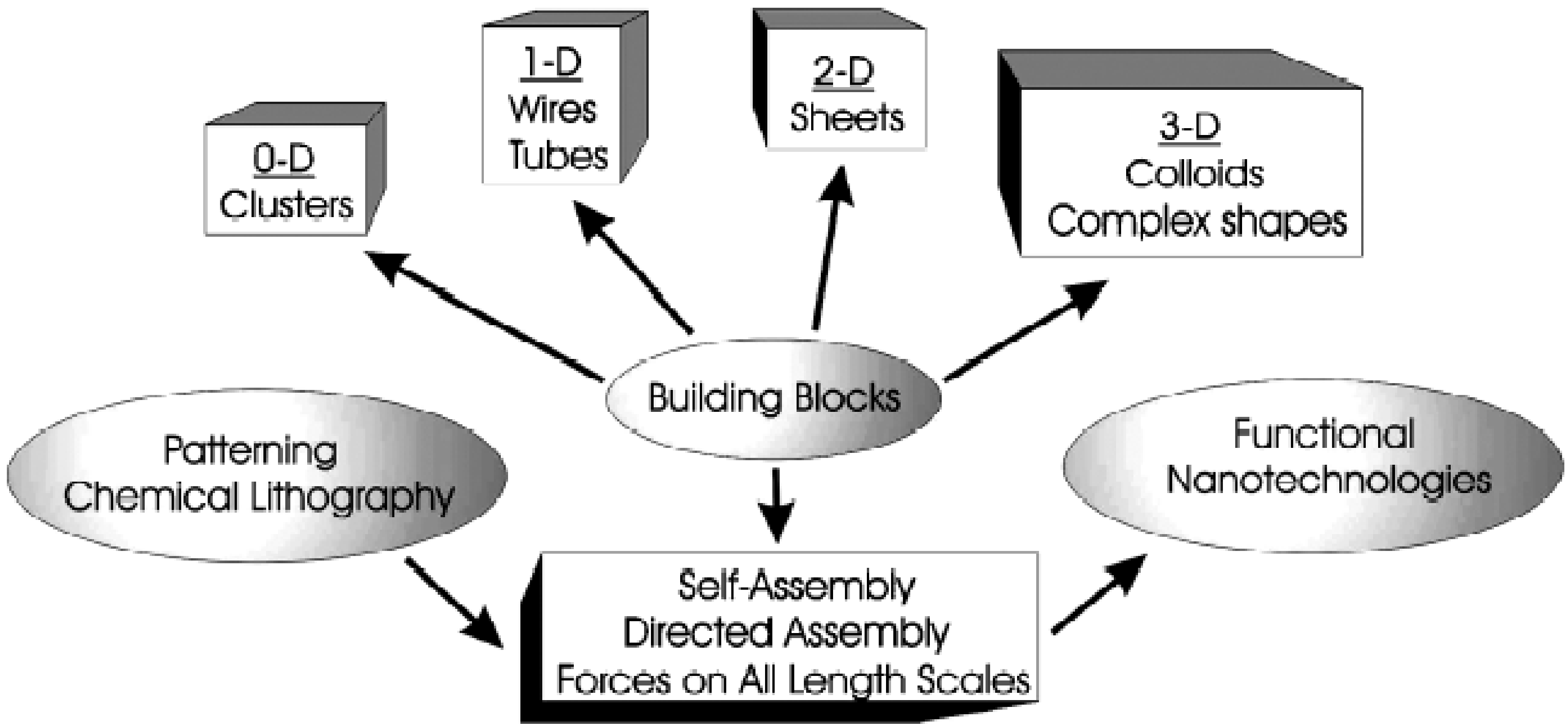


"Glued" 2D networks

Gu, Chen, Gracias. *Langmuir* 2004, *20*,11308.

nano manufacturing center at UML

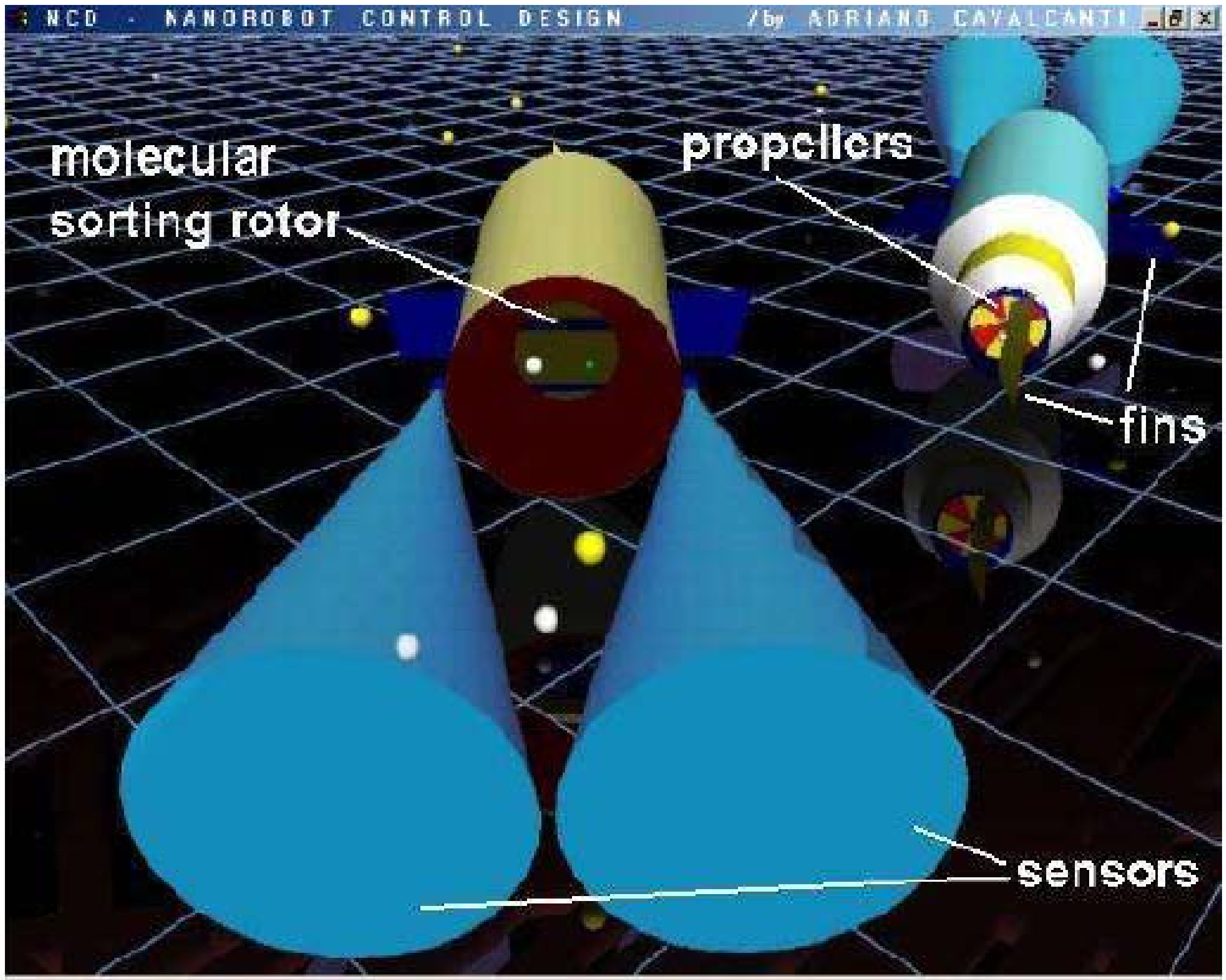
Self-assembling route to Nanotechnology



A flowchart delineating the factors that must be considered when approaching the self-assembly of a nanoscale system

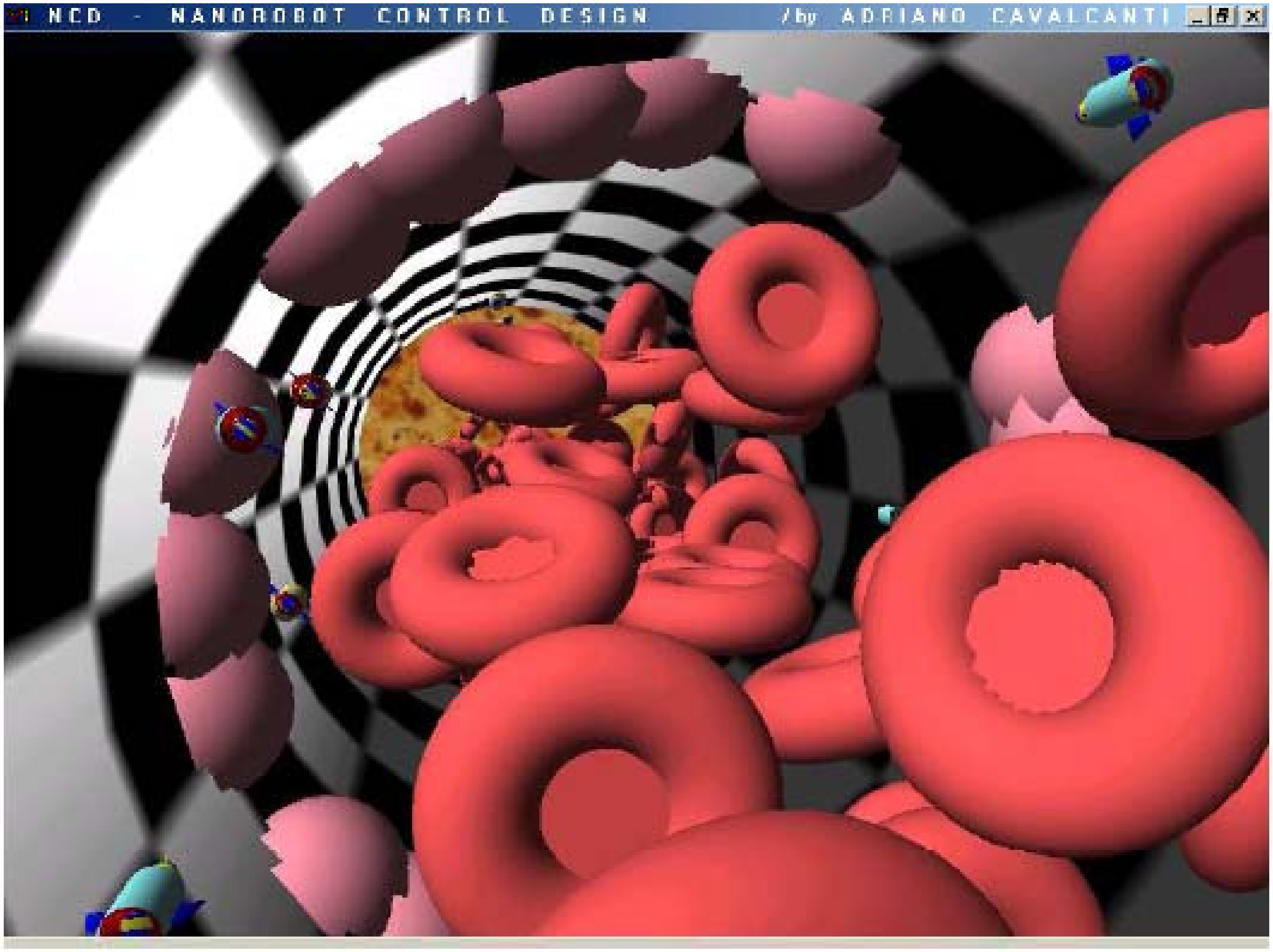
Ozin and Arsenault. Nanochemistry: A Chemical Approach to Nanomaterials. RSC Publishing, 2005

Nanorobots for Medicine (Surgery)



The depicted blue cones shows the sensors “touching” areas that triggers the nanorobots’ behaviors.

Nanorobots for Medicine (Surgery)



The atherosclerotic lesion was reduced due nanorobots activation.
The temperatures in the region turn in expected levels.

Next Lecture on May 1 – Last Lecture !

❖ May 1 (3:30-6pm): 1st half of final presentations (alphabetical order): 16 students

❖ May 7 (final exam time: 3-6pm): 2nd half of final presentations (alphabetical order): 17 students

❖May 7: Final report due (by emails)

❖ Room: KI302