Emerging Issues in Nanotechnology

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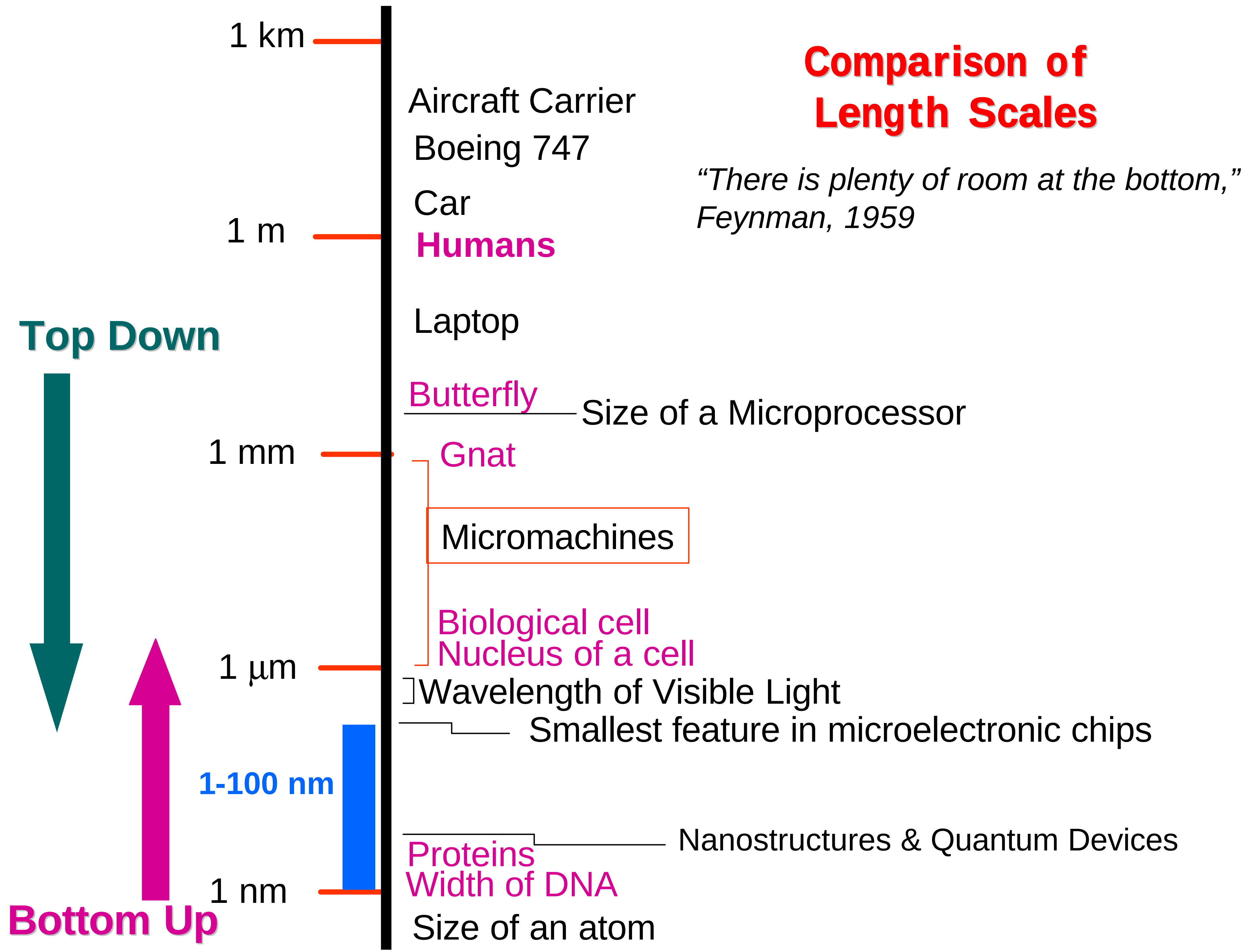

Comparison of Length Scales
"There is plenty of room at the bottom," Feynman, 1959
1 km
Aircraft Carrier
Boeing 747
Car
1 m
Humans
Top Down
Laptop
Butterfly
Size of a Microprocessor
1 mm
Gnat
Micromachines
Biological cell
Nucleus of a cell
1 µm
Wavelength of Visible Light
Smallest feature in microelectronic chips
1-100 nm
Nanostructures & Quantum Devices
Proteins
Width of DNA
1 nm
Bottom Up
Size of an atom

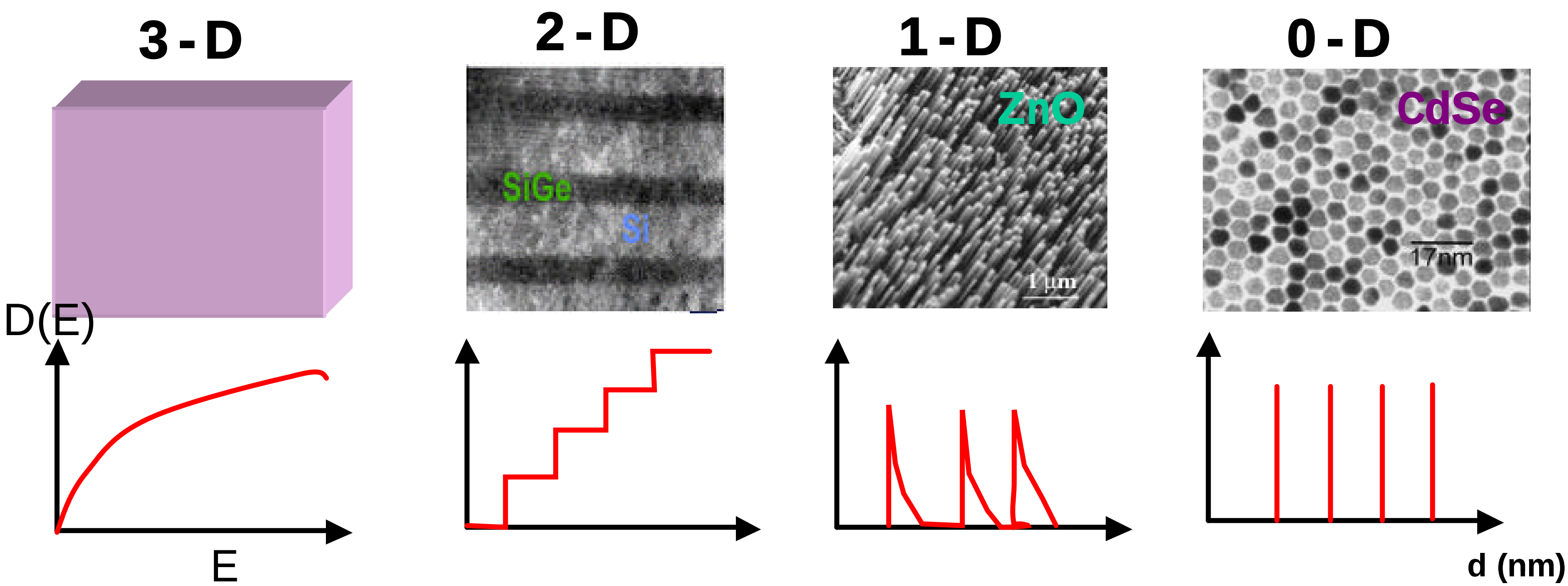
Why Miniaturize?

<100 nm

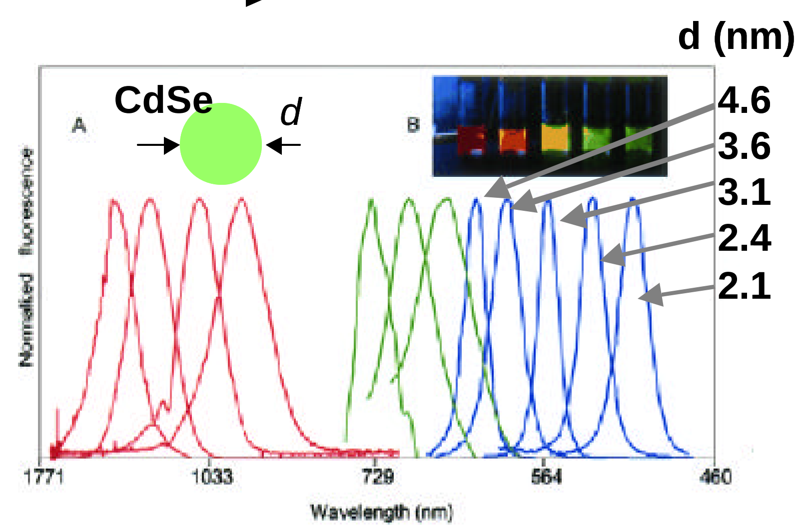
- Manipulate quantum effects in low-dimensional
  structures (quantum dots, wires, wells)
  electronic, optical, thermal, …
- Access new molecular effects
  (mechanics, electronics, recognition, …)
- High Surface to Volume Ratio

- Building Blocks
- Tools
- Integration
- Systems

Effects of Confinement of Charge Carriers

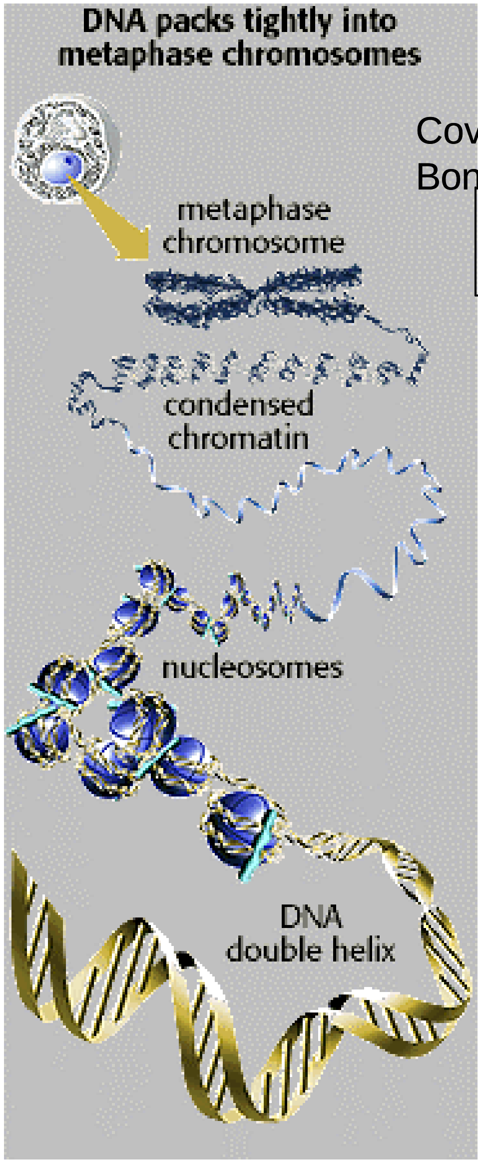


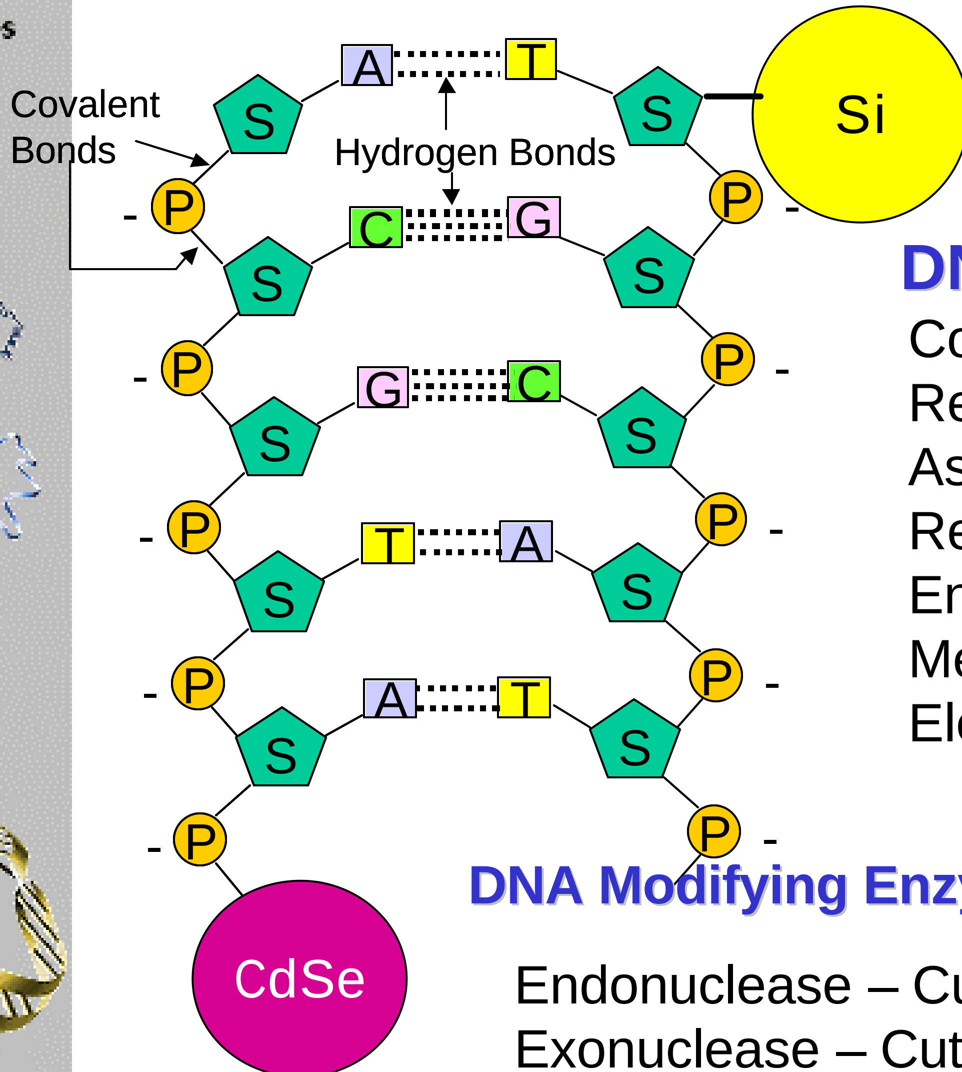
- What about phonon confinement?
- What about melting point?
- What about dislocation/defects?
- What about catalytic activity?



Courtesy: Paul Alivisatos, UCB

Molecular Effects





DNA Attributes

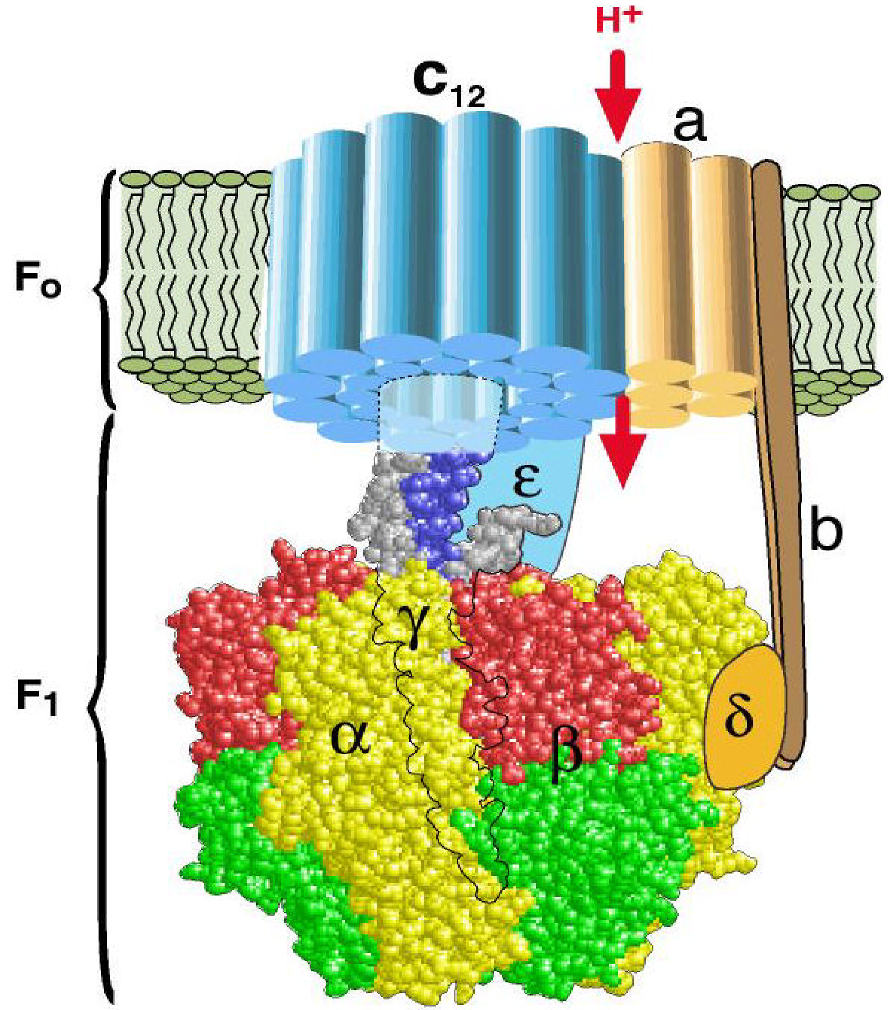
Coding & Information
Recognition
Assembly
Replication
Entropy
Mechanics & Actuation
Electrical Conductor

DNA Modifying Enzymes – The Tool Box

Endonuclease – Cuts in the middle
Exonuclease – Cuts from the end
Ligase – Joins gaps in DNA
Polymerase – Builds complem. sequence

What about other molecules?

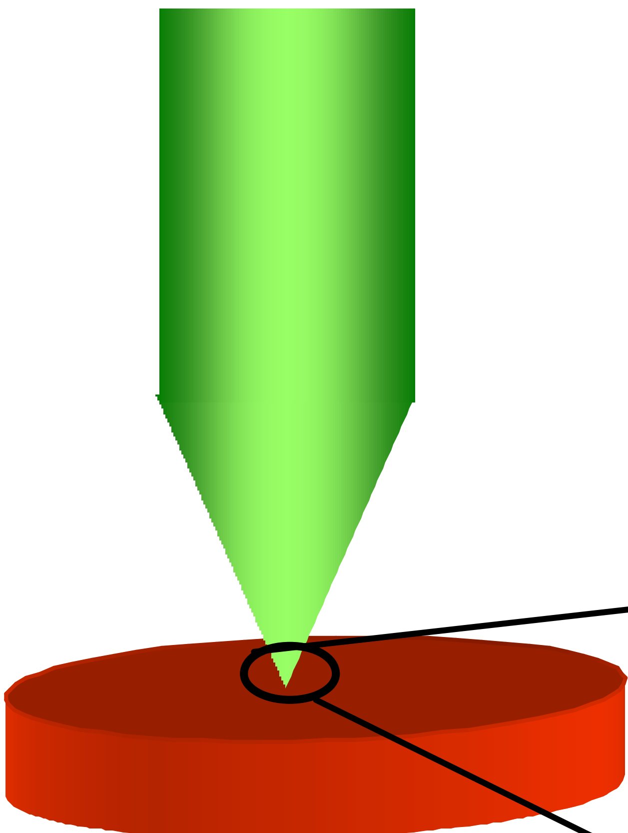
Molecular Motors

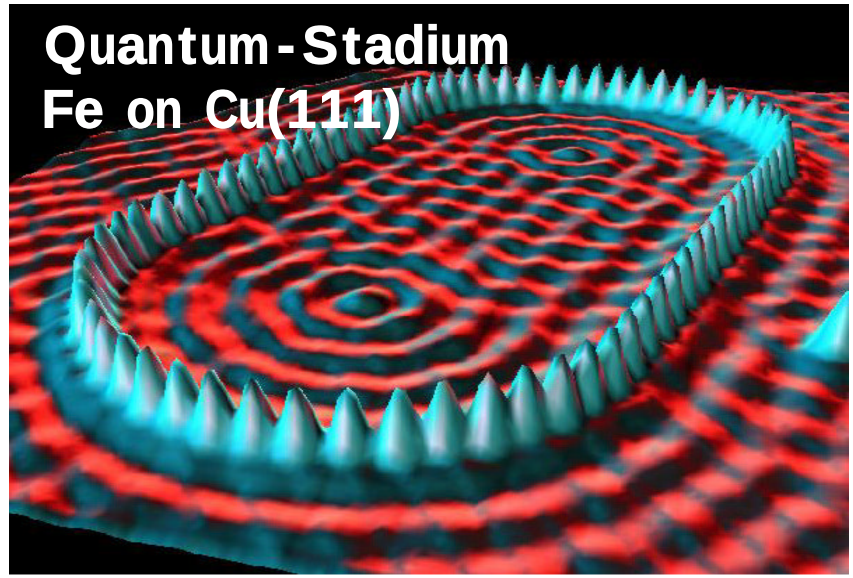


ATP Synthase

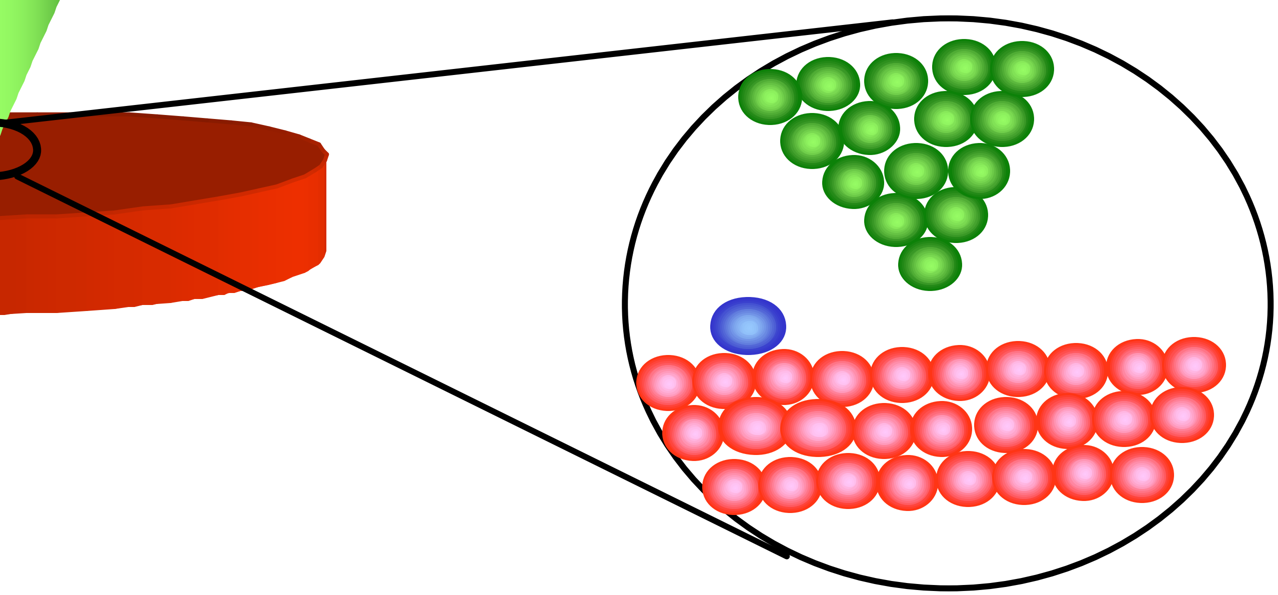
Nanotools

Scanning Tunneling Microscope



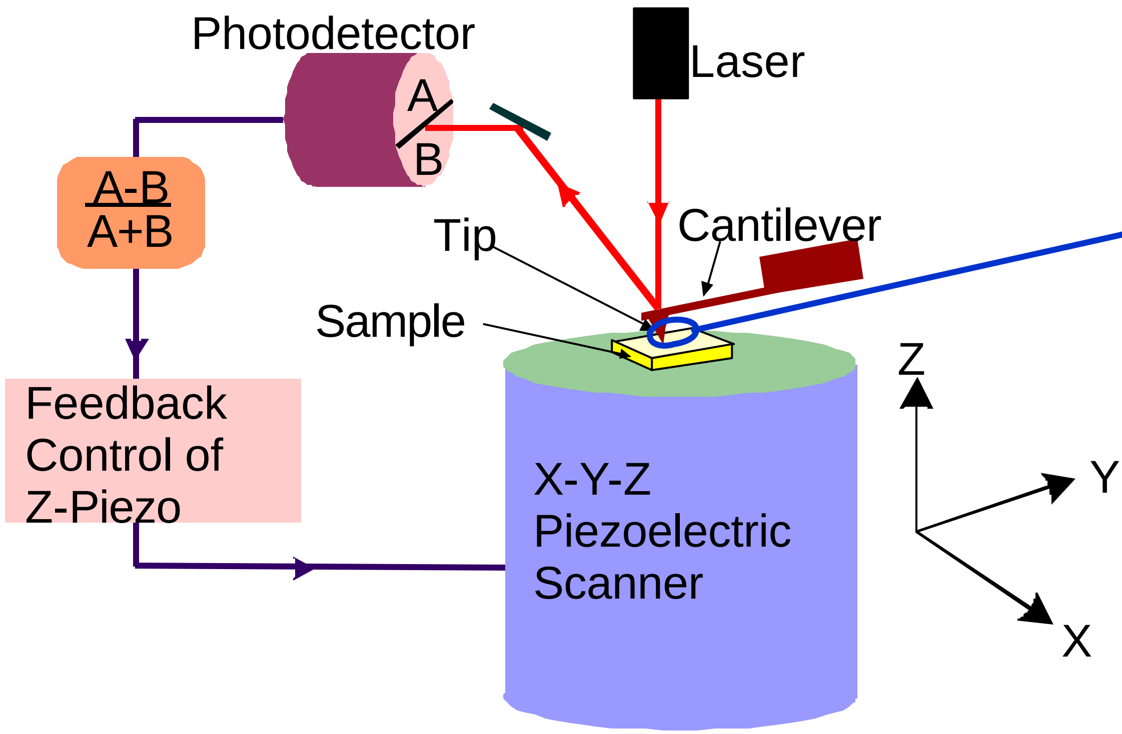


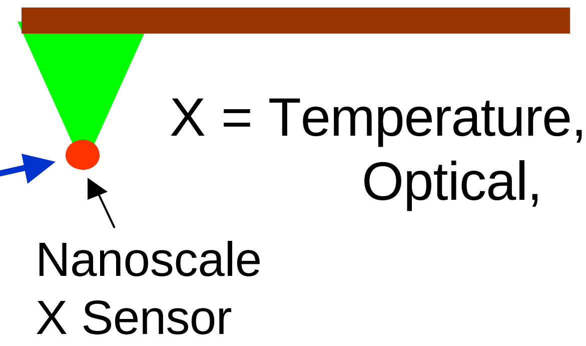
Courtesy: IBM Almaden Lab



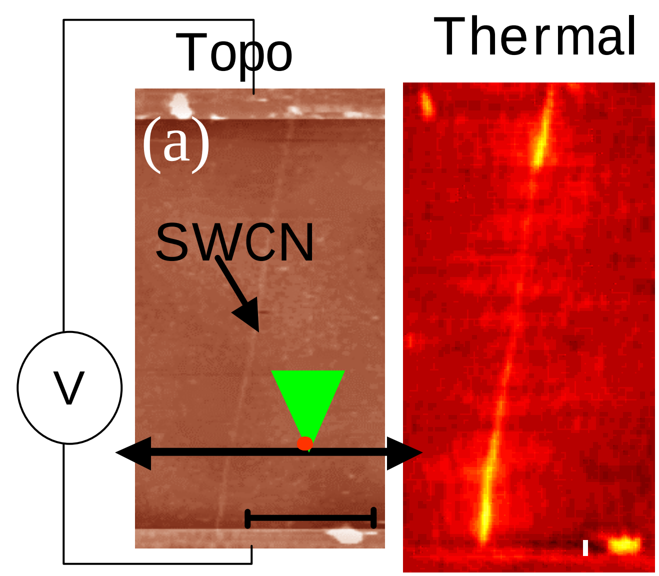
Nanotools

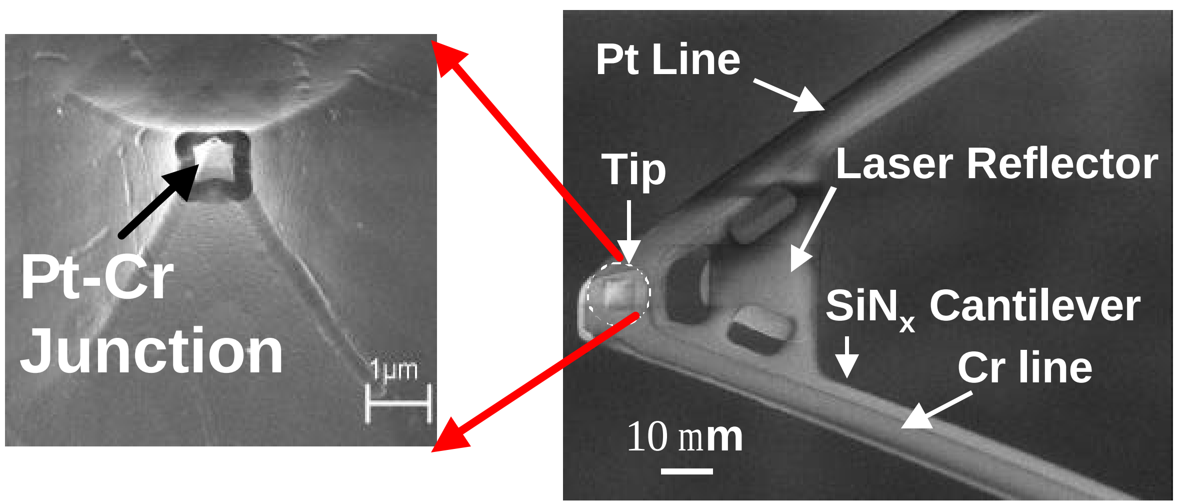
Atomic Force Microscope



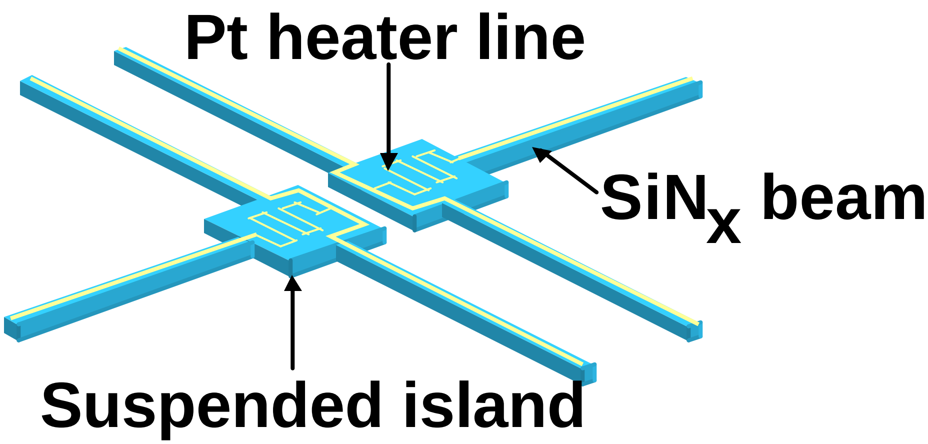


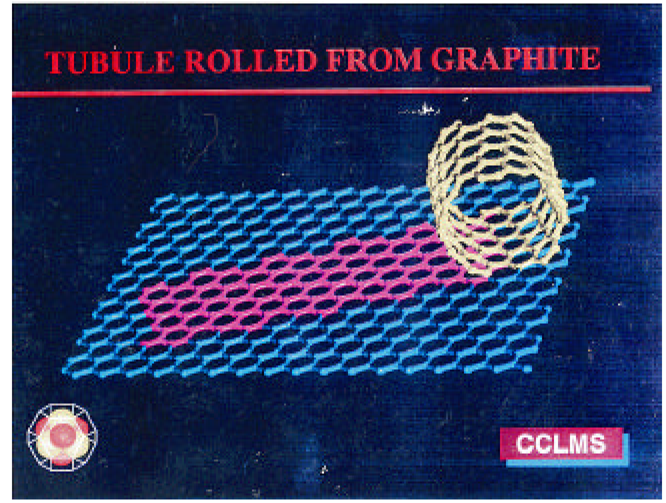
Single Wall Carbon Nanotube

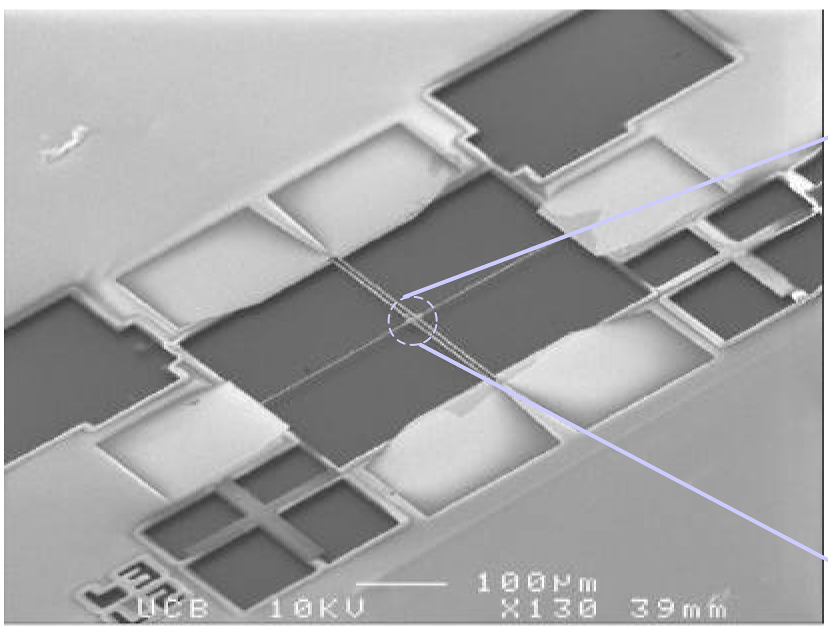


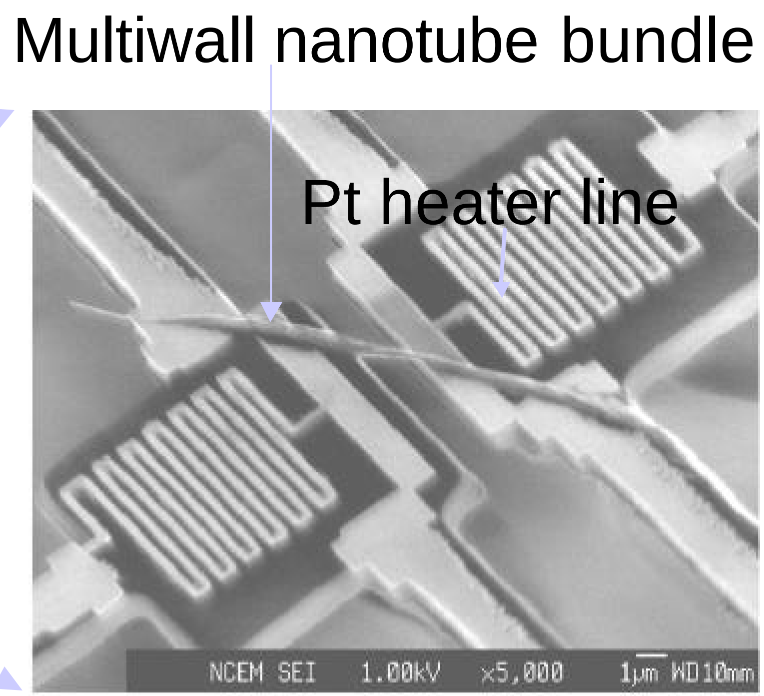


Nanotube-MEMS Hybrid Device

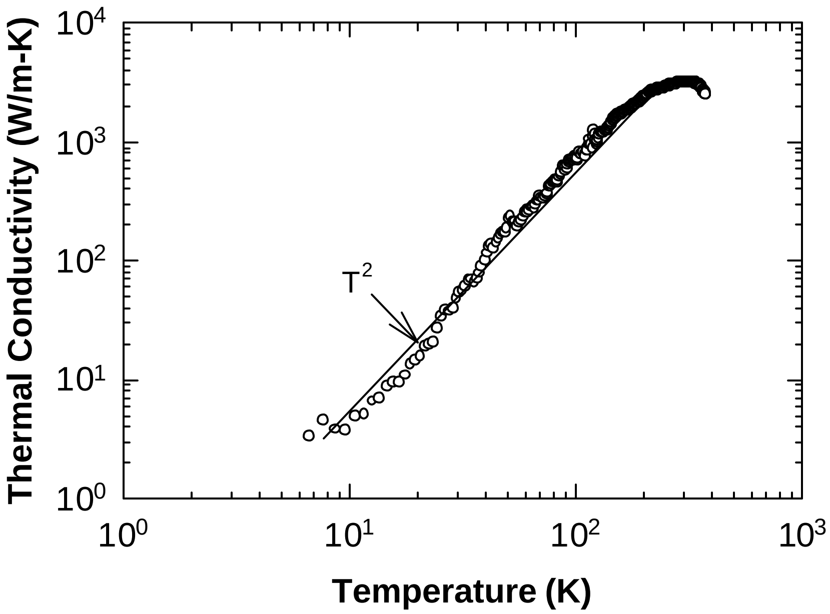


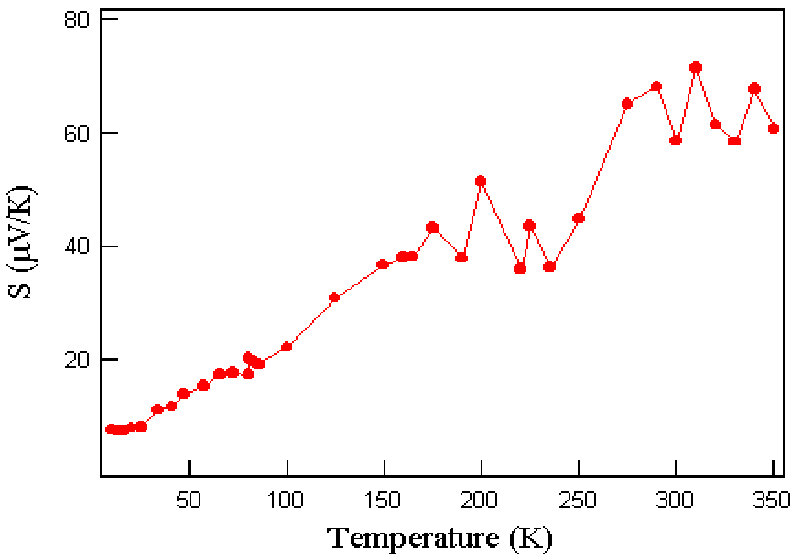


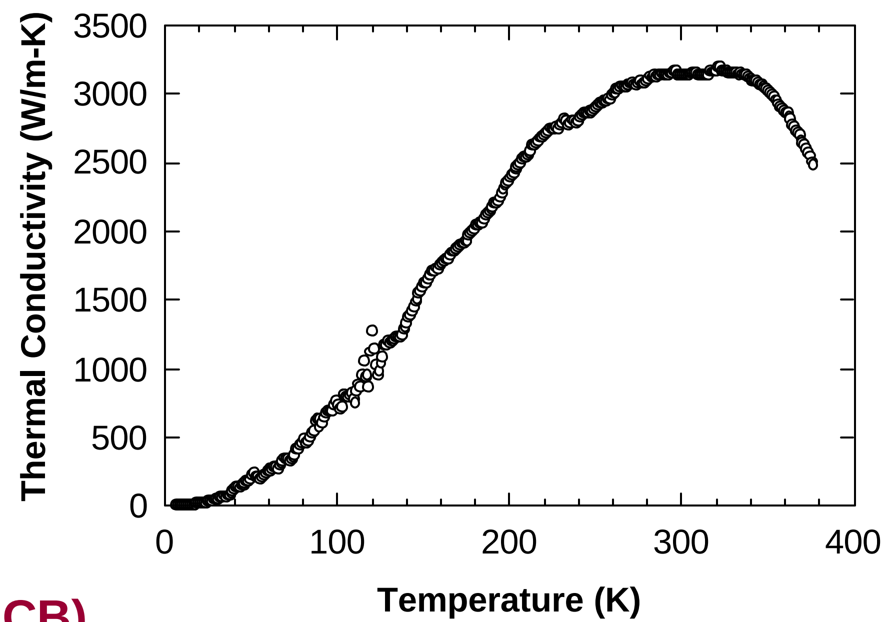




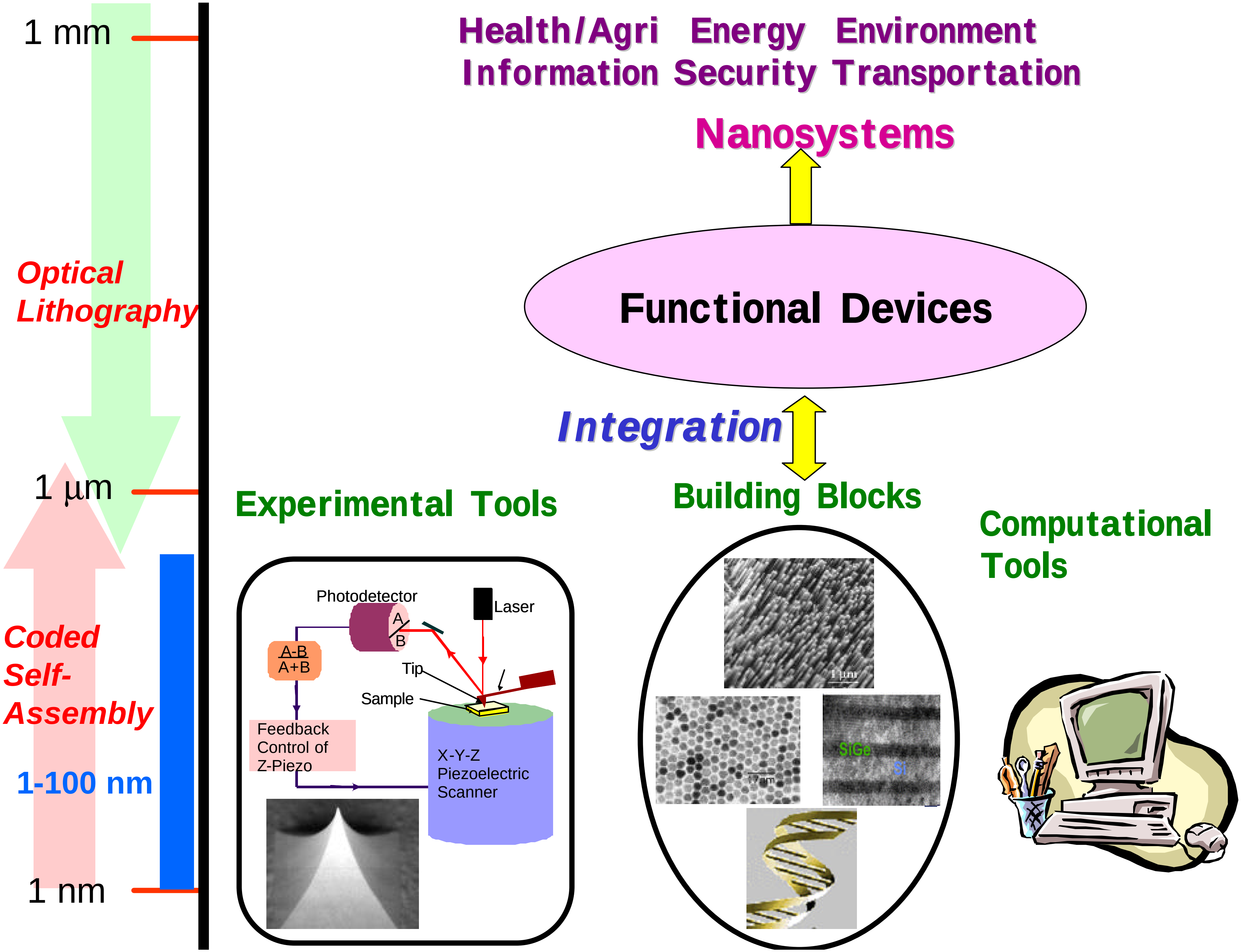
Thermal Conductivity & Thermopower







- Li Shi (ME,UCB)
- Philip Kim, Paul McEuen (Physics, UCB)



1 mm
Optical Lithography
1 µm
Coded Self-Assembly
1-100 nm
1 nm
Health/Agri Energy Environment
Information Security Transportation
Nanosystems
Functional Devices
Integration
Experimental Tools
Building Blocks
Computational Tools
Photodetector
Laser
A
B
A-B
A+B
Tip
Sample
Feedback Control of Z-Piezo
X-Y-Z Piezoelectric Scanner
SiGe
Si

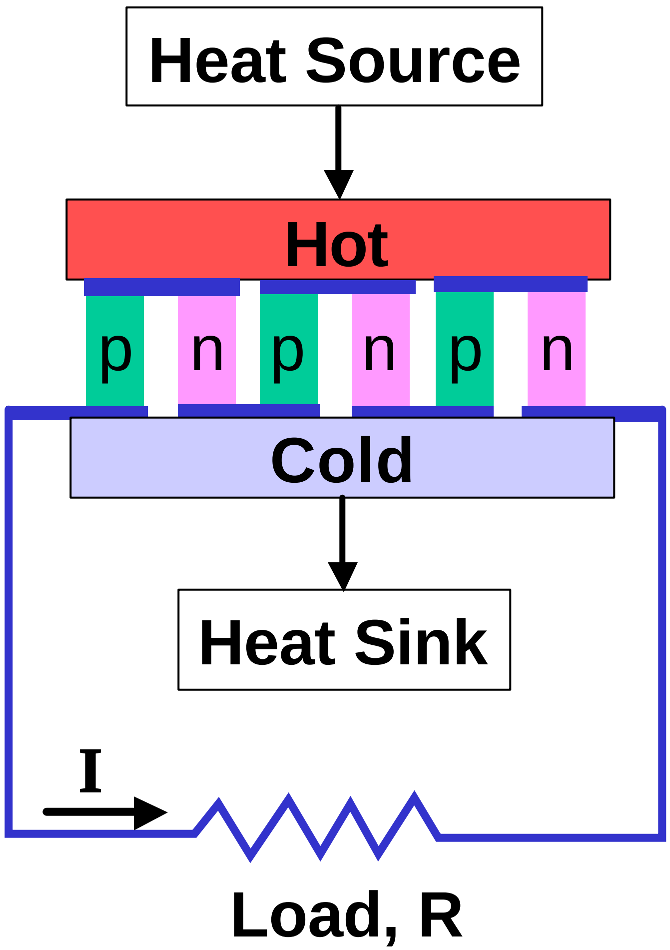
Outline

- **Energy Conversion**

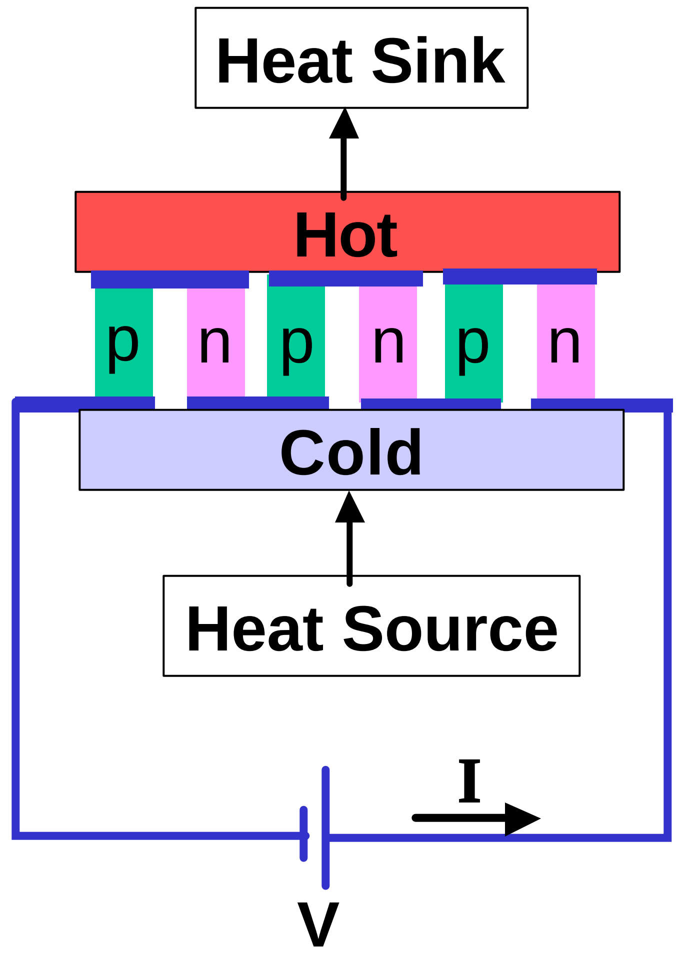
- **Health and Biomedical**

Solid-State Thermoelectric Energy Conversion

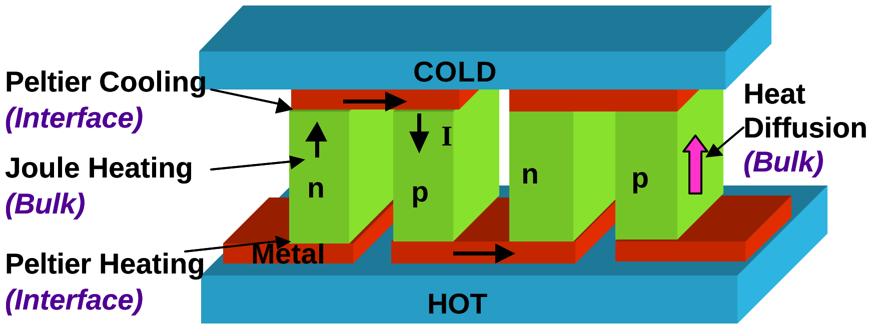
Engine



Refrigerator



Solid-State Energy Conversion

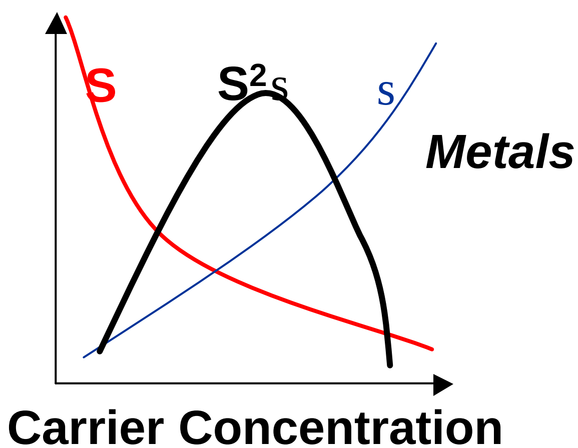


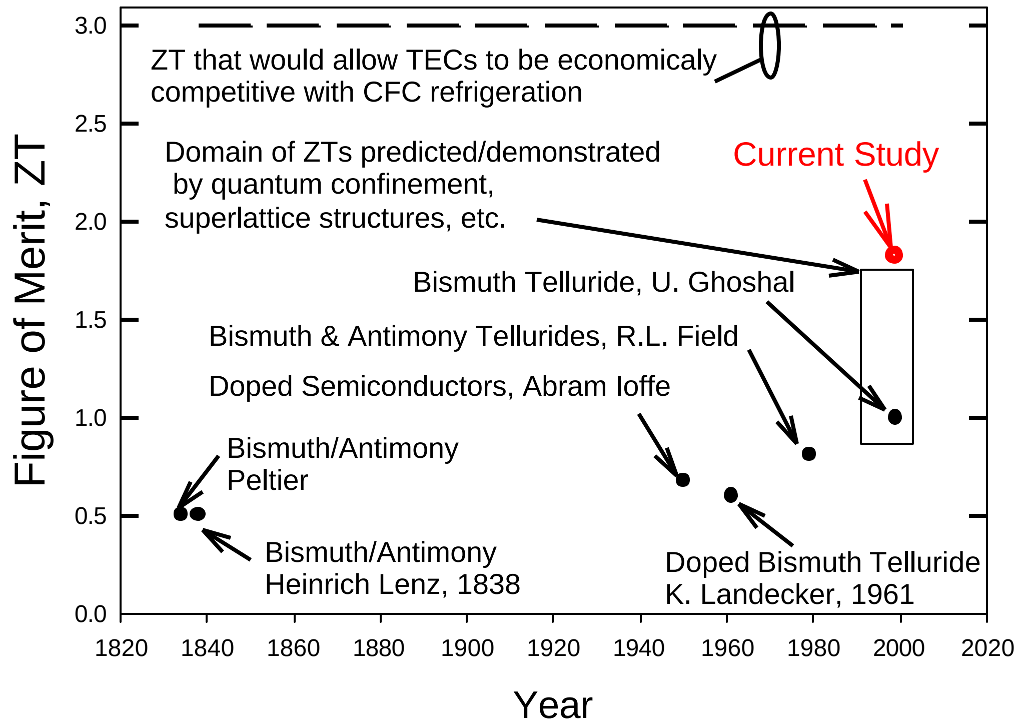
$$ZT = \frac{S^2 \sigma T}{k}$$

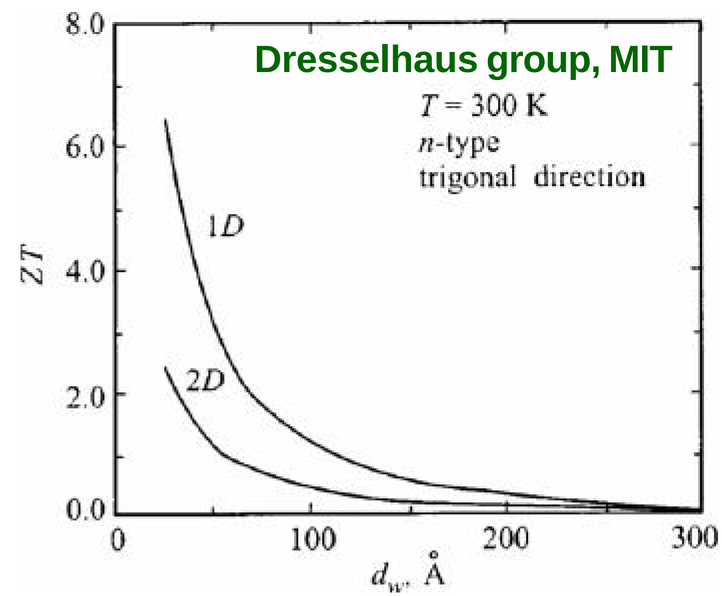
Thermoelectric Figure of Merit

S: Seebeck Coeff.

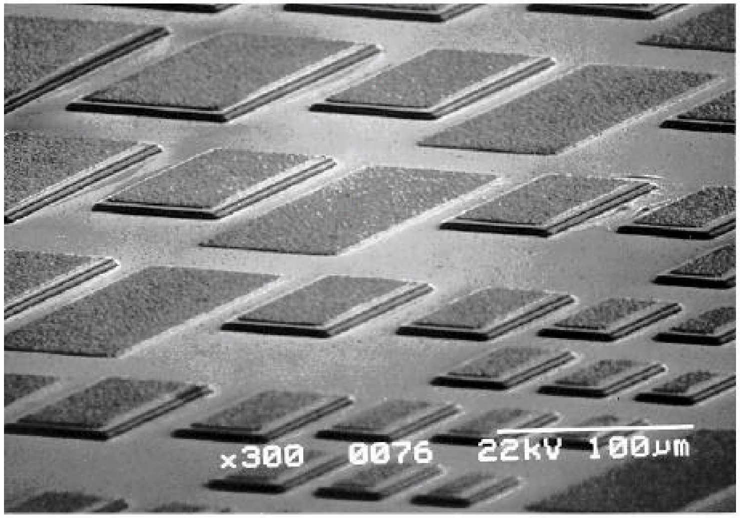
σ: Electrical Conductivity



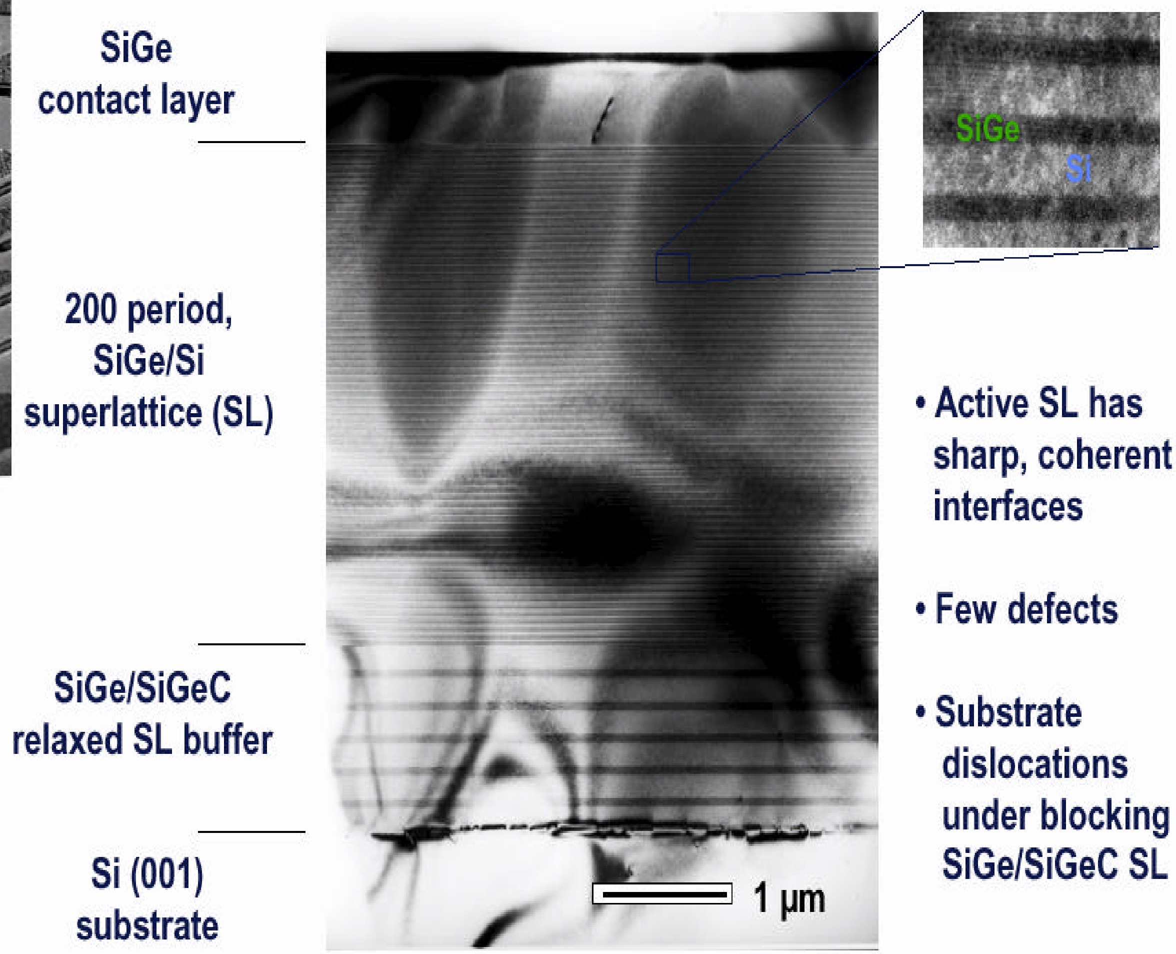




SiGe Integrated Thermoelectric Refrigerators



Cross-sectional TEM

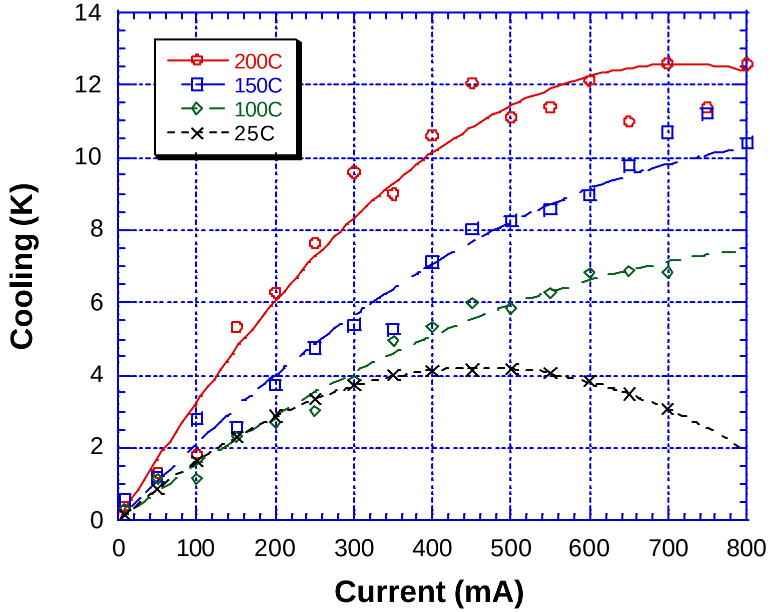


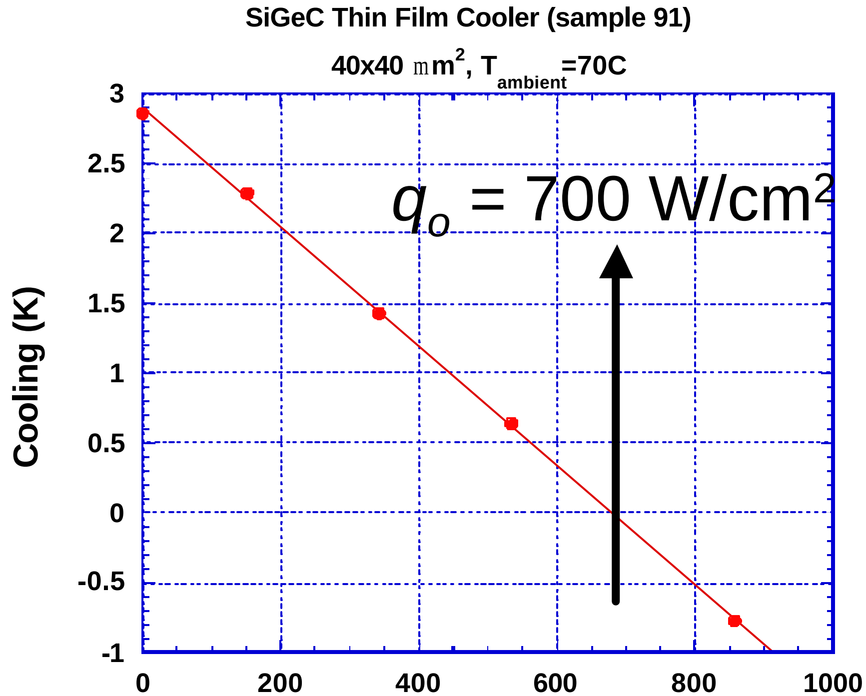
- Active SL has sharp, coherent interfaces
- Few defects
- Substrate dislocations under blocking SiGe/SiGeC SL

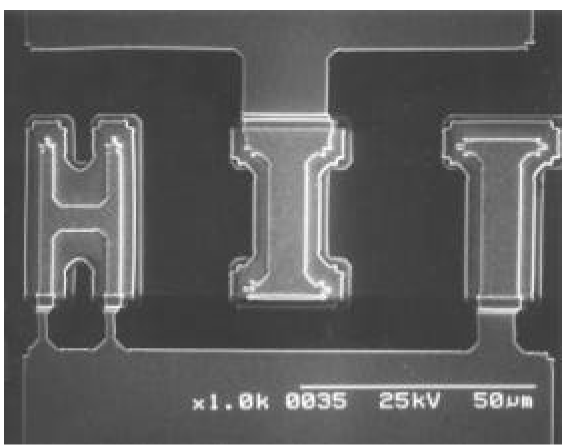
$$ZT = \frac{S^2 \sigma T}{k}$$

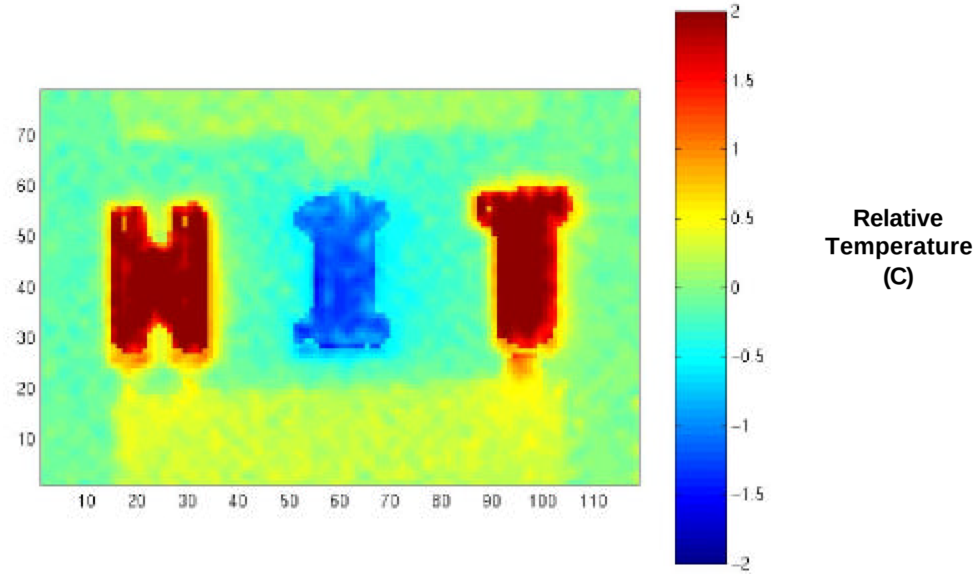
Collaboration: John Bowers (ECE, UCSB); Ali Shakouri (ECE, UCSC);
Ed Croke (Hughes Res. Lab.); Venky Narayanamurti (Dean, Harvard)

Device Performance





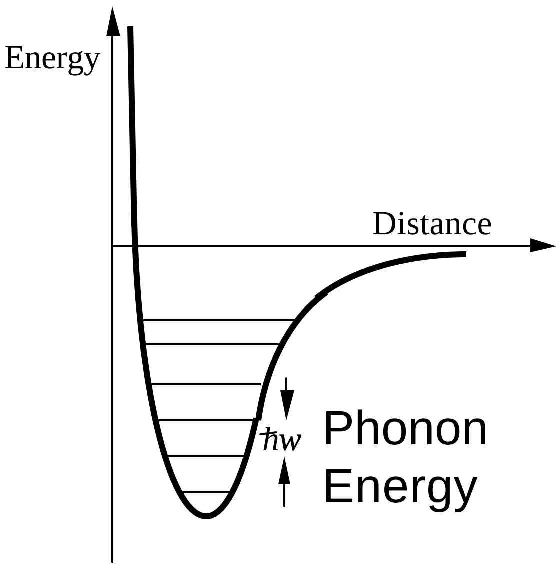


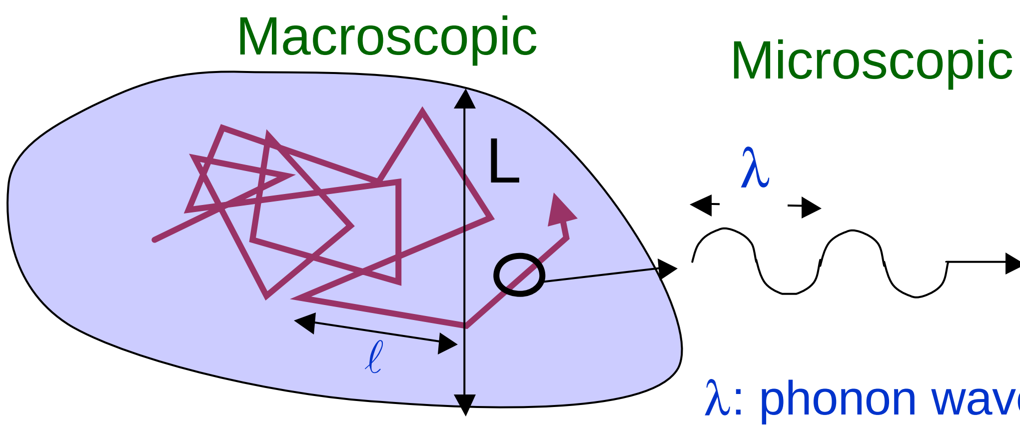


Courtesy: Ali Shakouri, UCSC

Energy Transport and Conversion in Semiconductors

Phonons in Semiconductors and Insulators

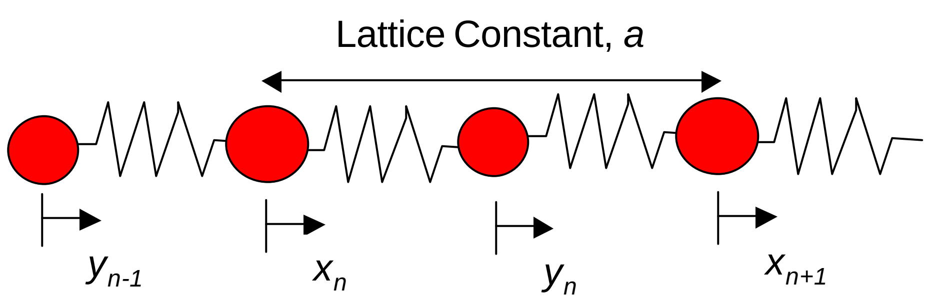




λ: phonon wavelength

$q = -k\nabla T$
$k = Cv\ell/3$

T: Temp. defined over a length scale larger than ℓ



Room Temperature Values

ℓ » **10-50 nm**

l » **1-10 nm**

Thermal Conductivity of Superlattices: Si/SiGe

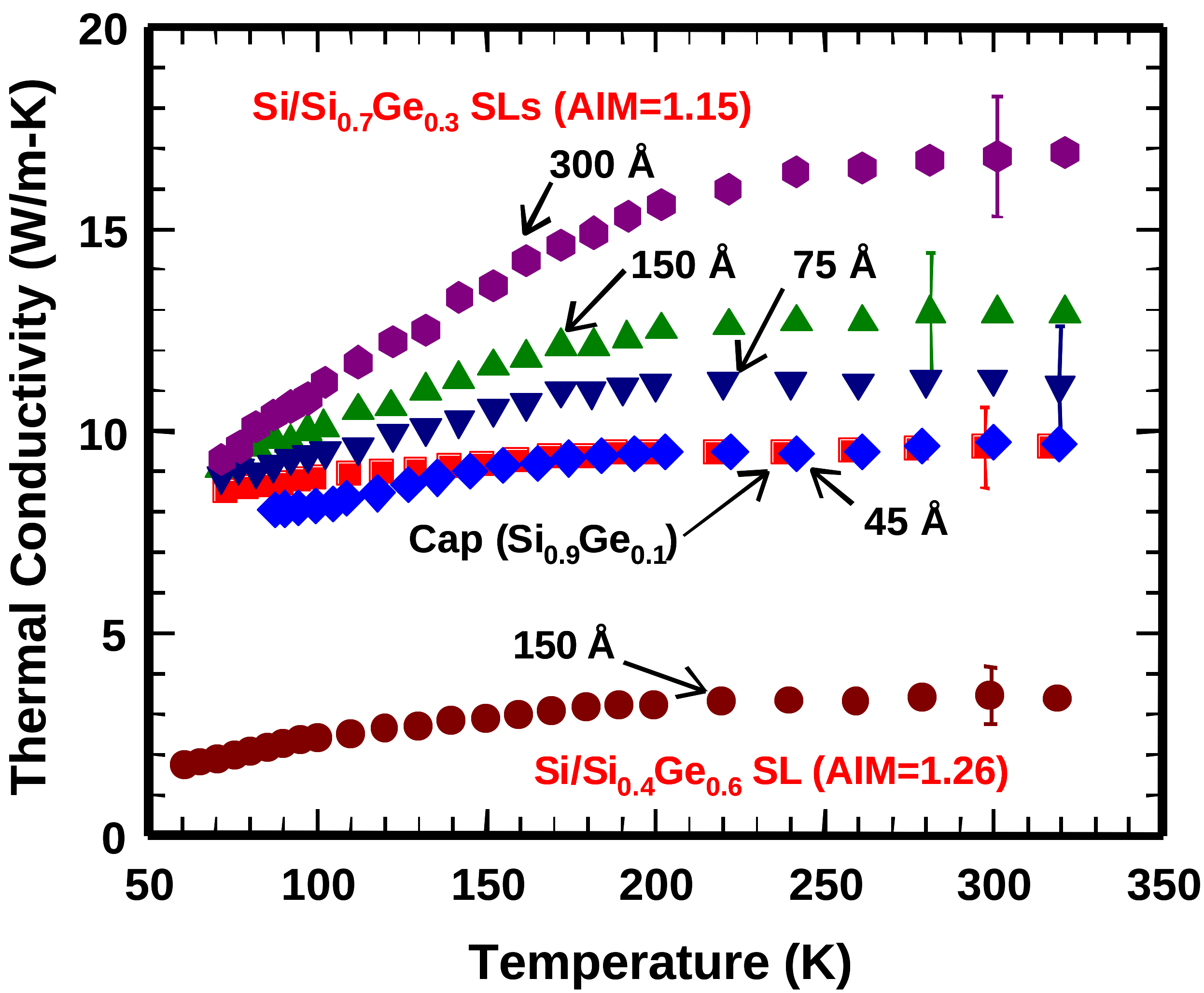
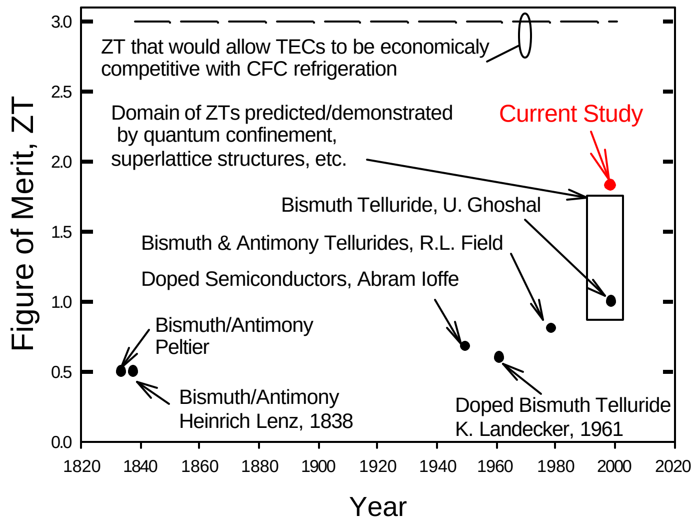
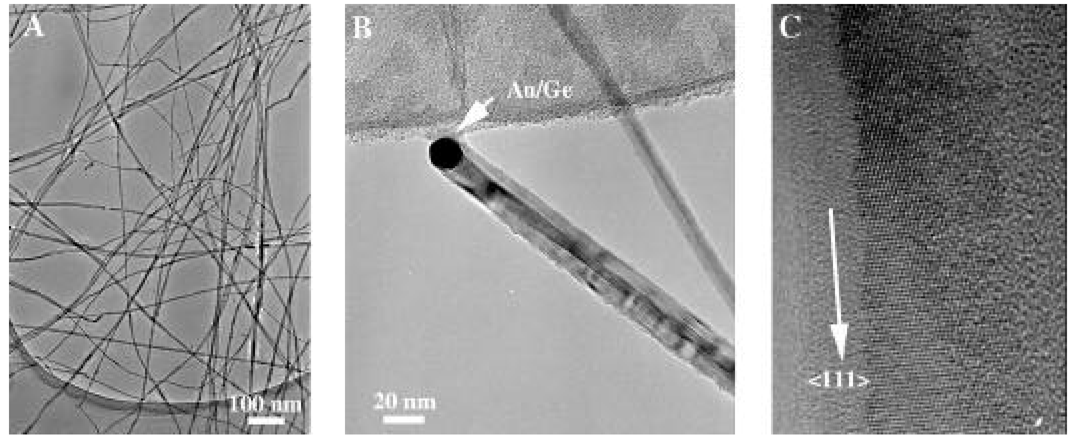
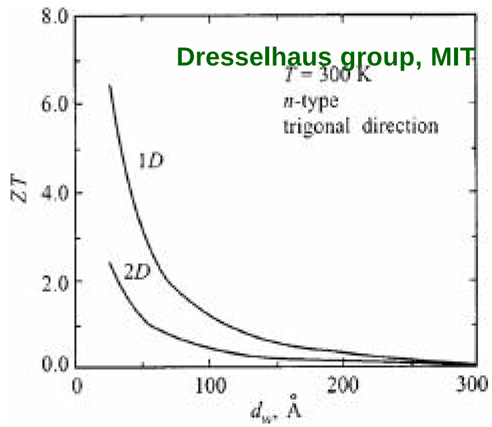


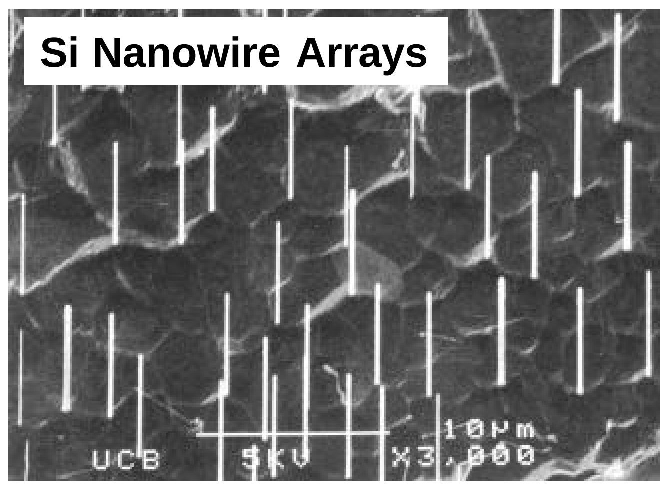
Figure 1: Thermal conductivity of Si/SiGe superlattices.

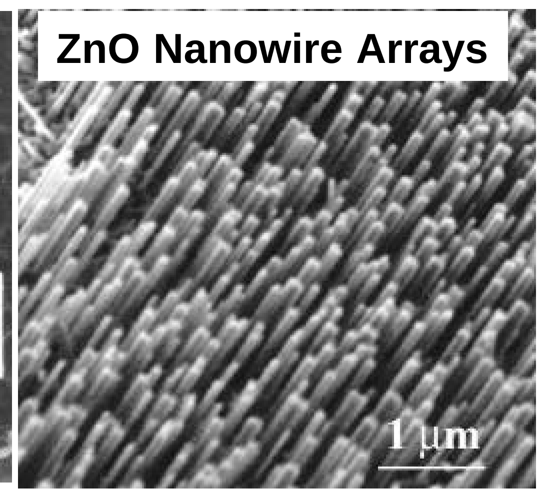
Semiconductor Nanowires







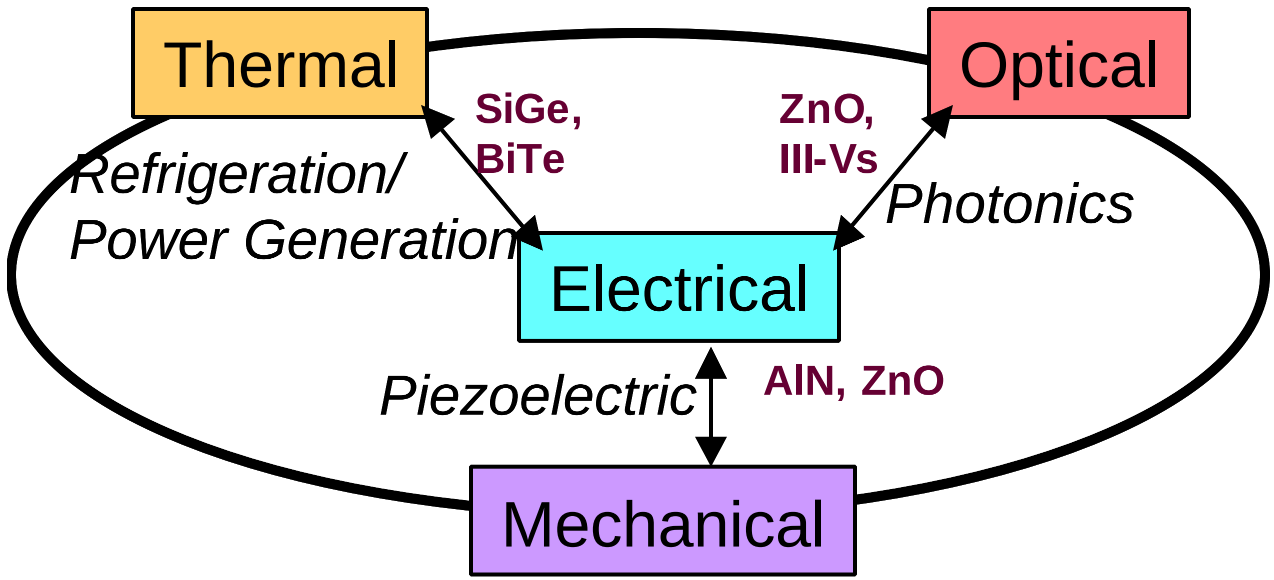




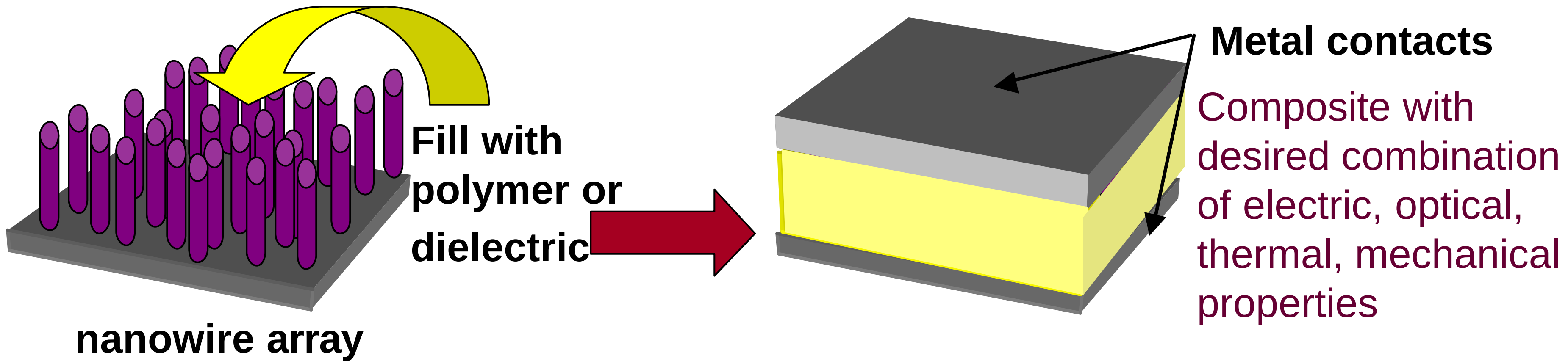
Collaboration: Peidong Yang (Chemistry, UCB), Ali Shakouri (EE, UCSC), Tim Sands (Matl. Sci, UCB), Venky Narayanamurti (Harvard), Arun Majumdar (ME, UCB)

Novel Energy Conversion Devices Based on Nanowire Heterostructures (NSF, Nanoscale Interdisciplinary Research Team)

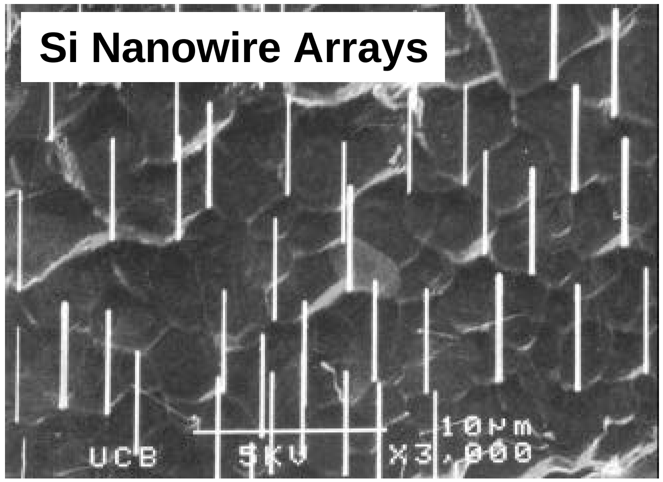
Energy Conversion Based on Nanowires

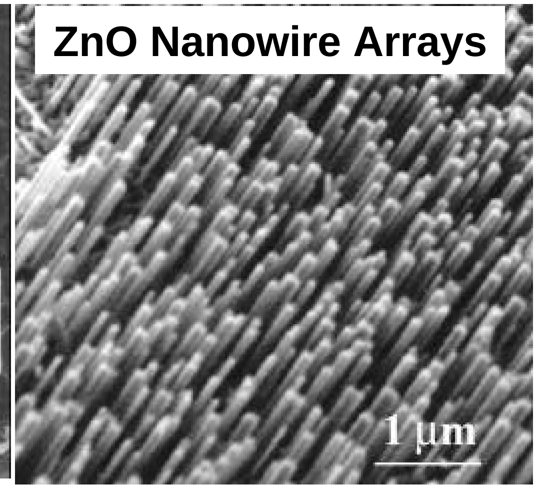


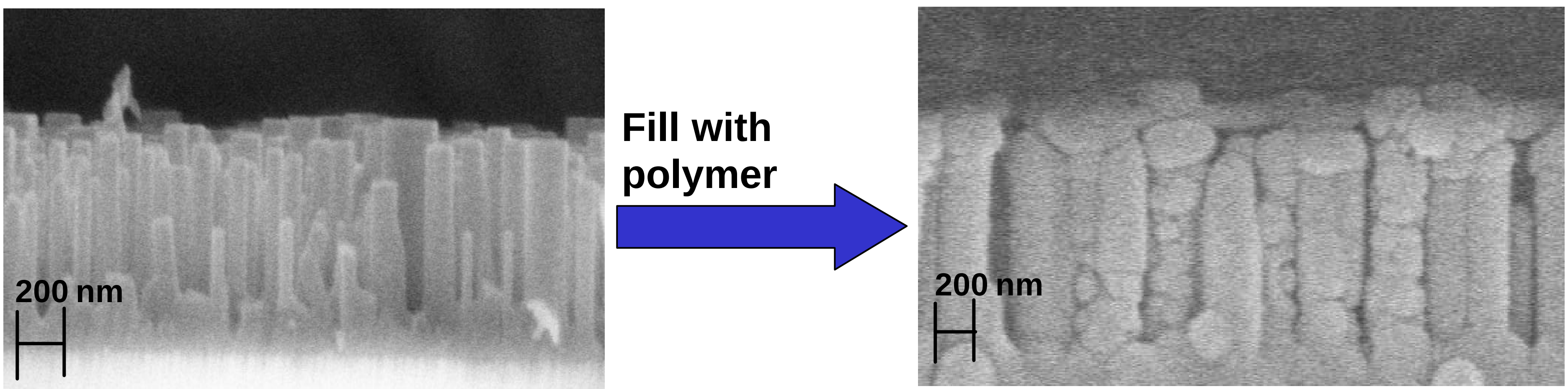
Nanowire Composite Platform (Heterogeneous Integration)



Nanowire Composites







ZnO Nanowire Array

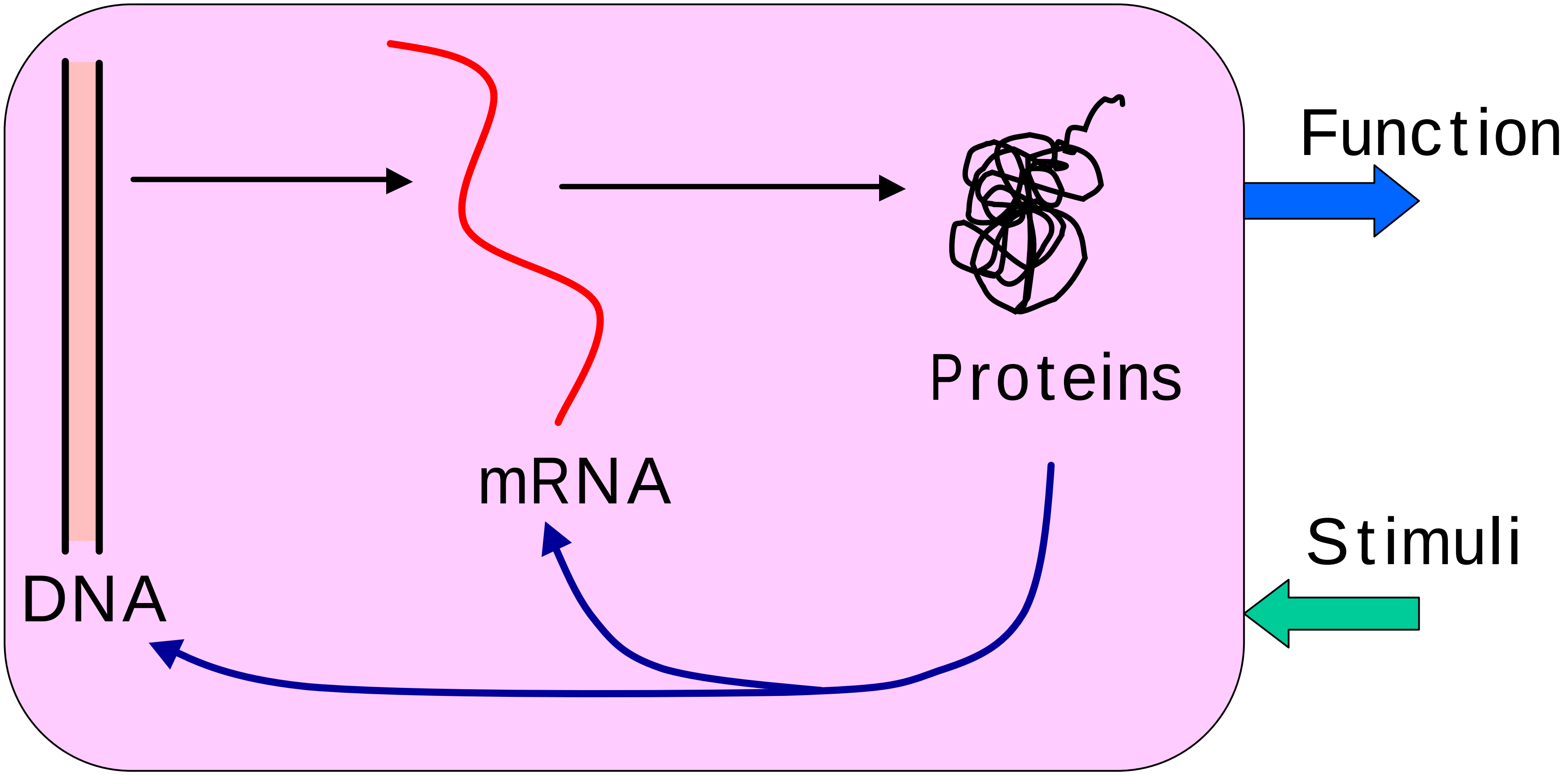
ZnO Nanowire Array partially filled with parylene

Outline

- **Energy Conversion**

- **Health and Biomedical**

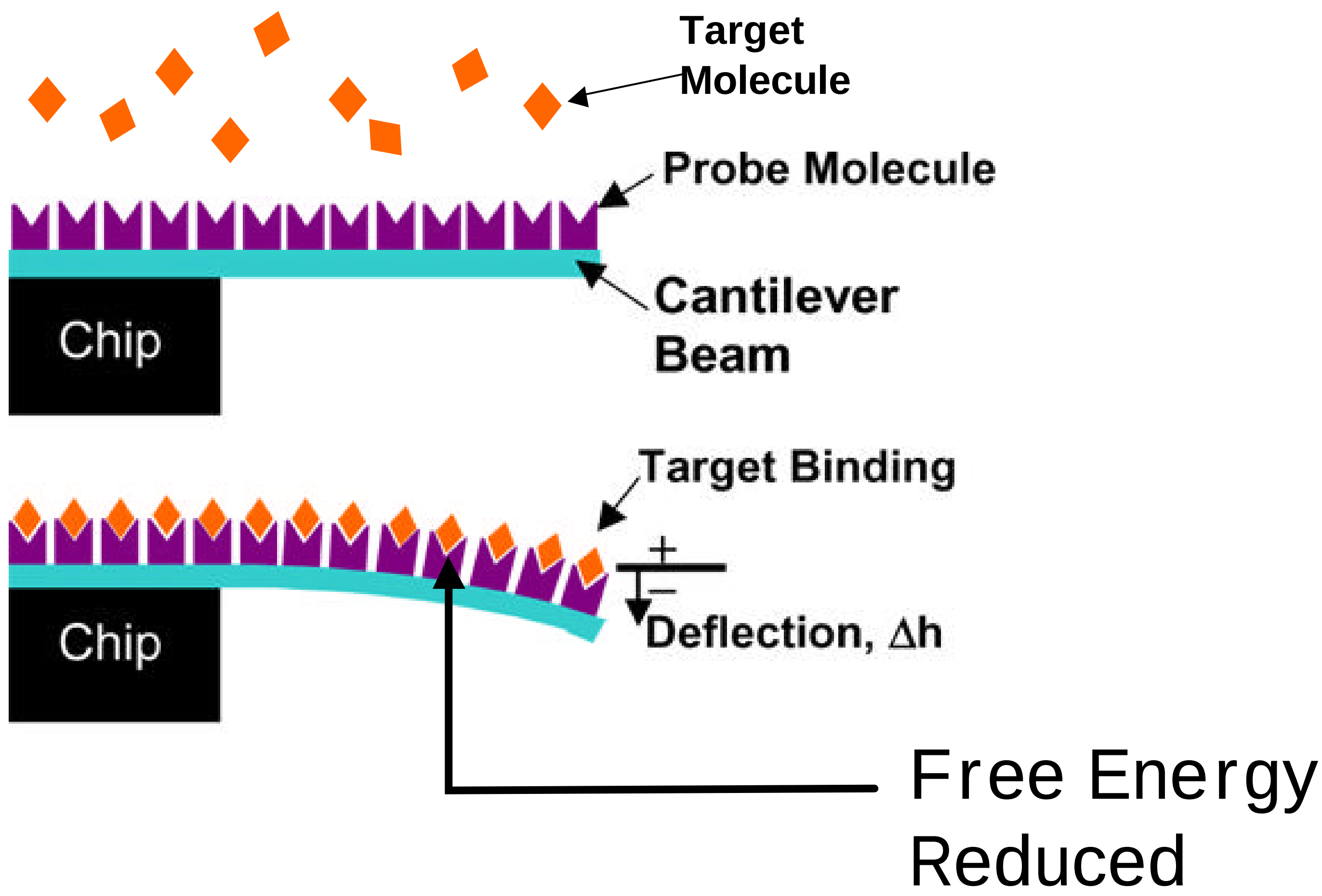
Dogma of Molecular Biology



A + B ⟷ C

Free Energy is Reduced

Motion from Biomolecular Interactions



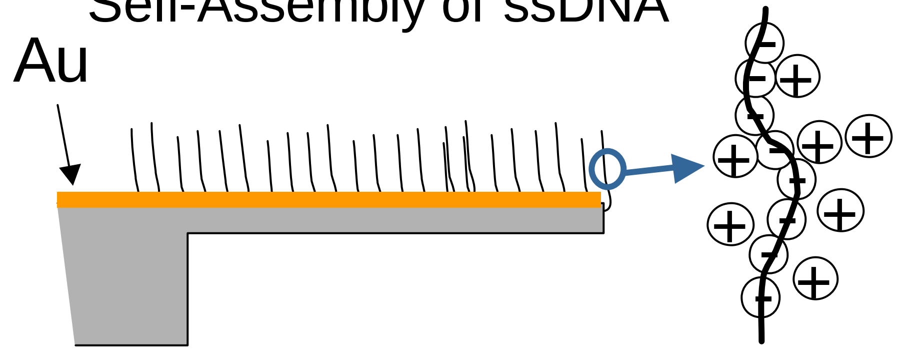
Immobilization of Single-Stranded DNA on Cantilever

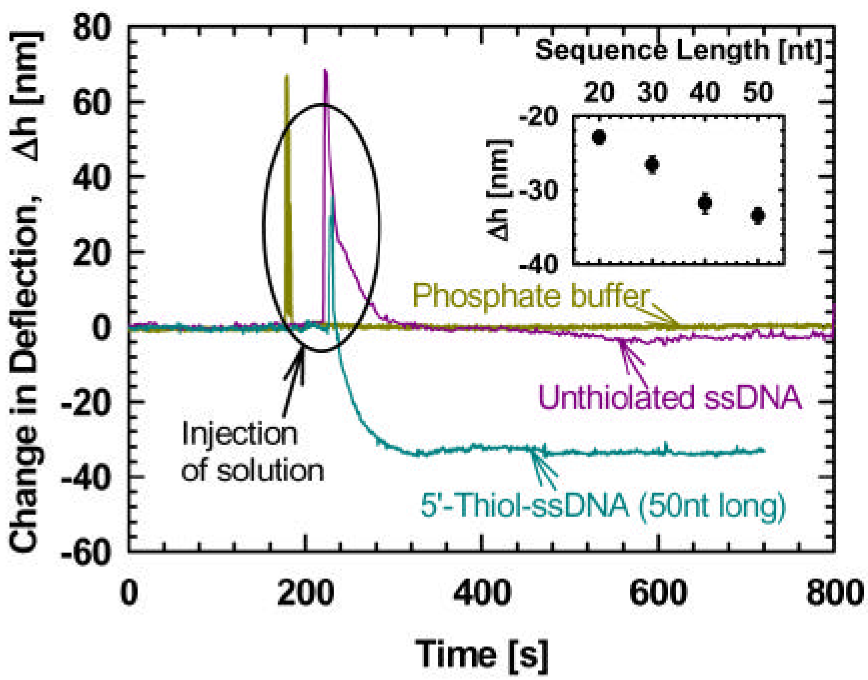
Thiolated ssDNA

5'-HS—ATCCGCATTACGTCAATC

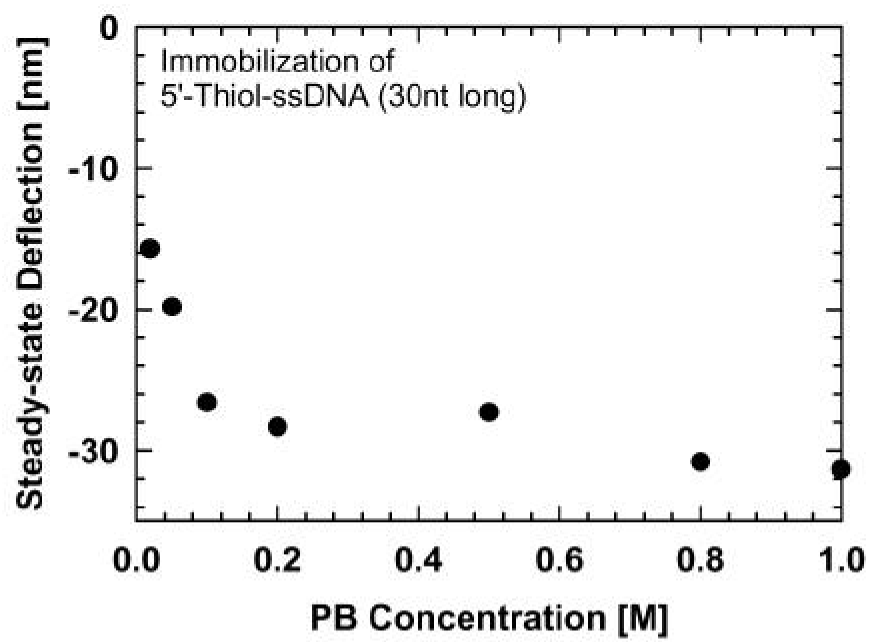
TAGGCGTAATGCAGTTAG-5'
(Complementary Strand)

Self-Assembly of ssDNA



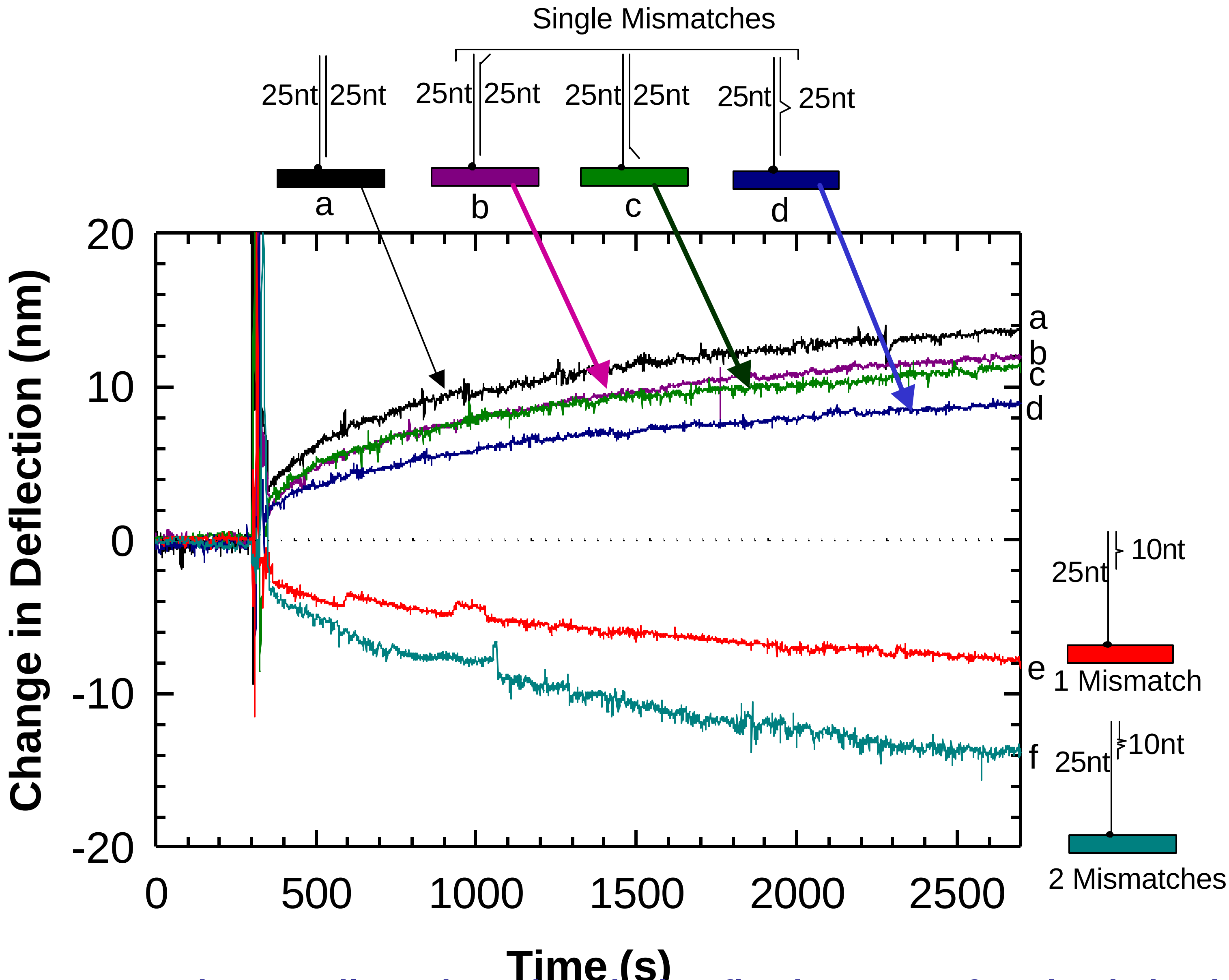


PB = Sodium Phosphate Buffer Solution



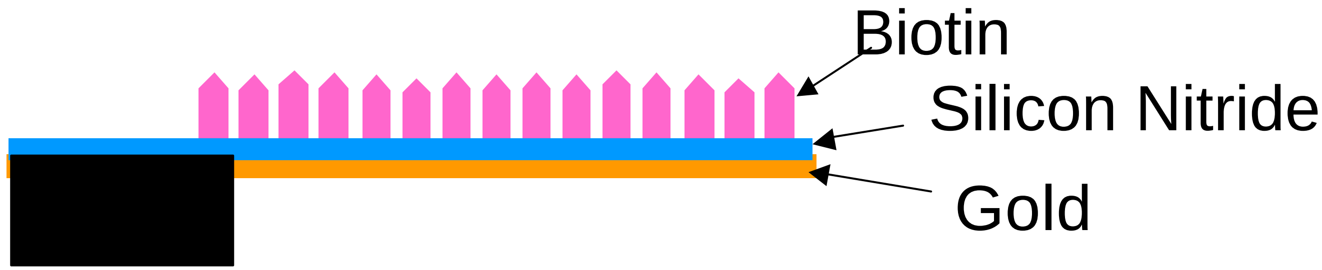
Wu, G. *et al.* "Origin of nanomechanical cantilever motion generated from biomolecular interactions," *PNAS* 98(4), 1560-1564 (2001).

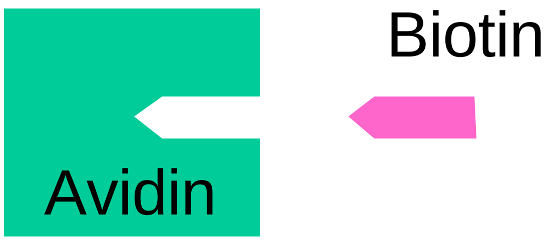
Nanomechanics of Base Pair Mismatches



Hansen, K. *et al*., "Cantilever-based Optical Deflection Assay for Discrimination of DNA Single Nucleotide Mismatches," *Analytical Chemistry*, Vol. 73, pp. 1567-1571 (2001).

Protein-Ligand Binding

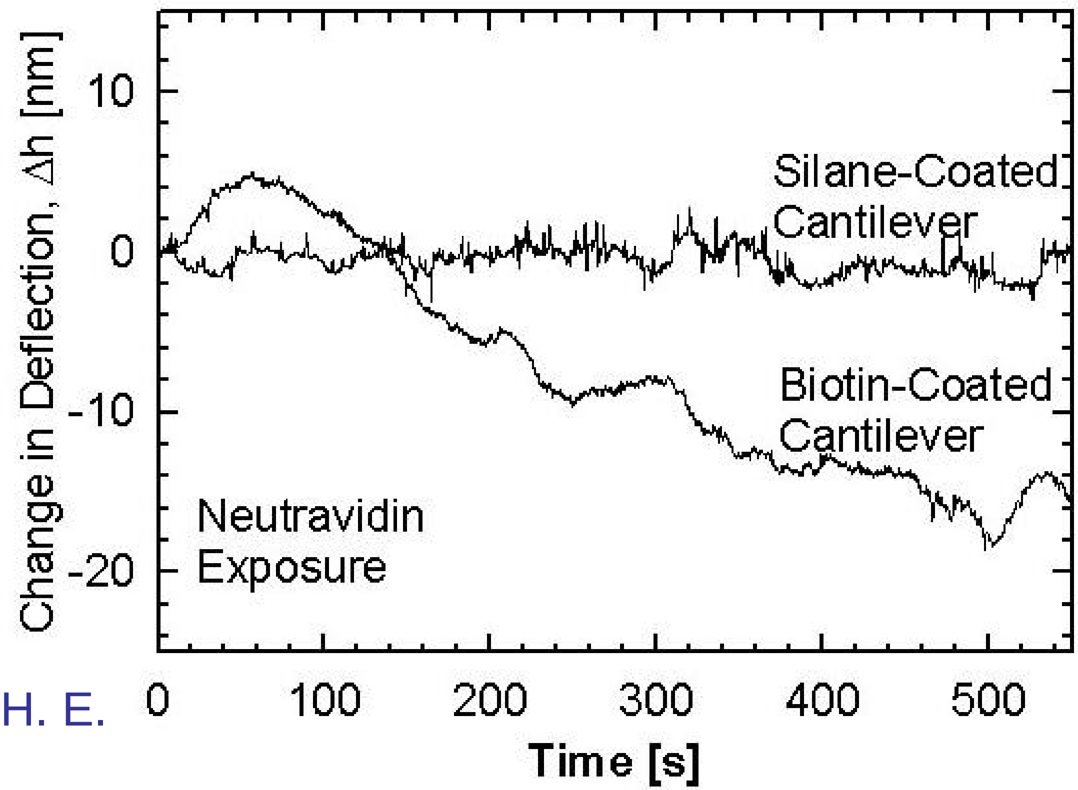




$F_{binding} \propto \Delta H$

$F_{binding} \neq \Delta G$

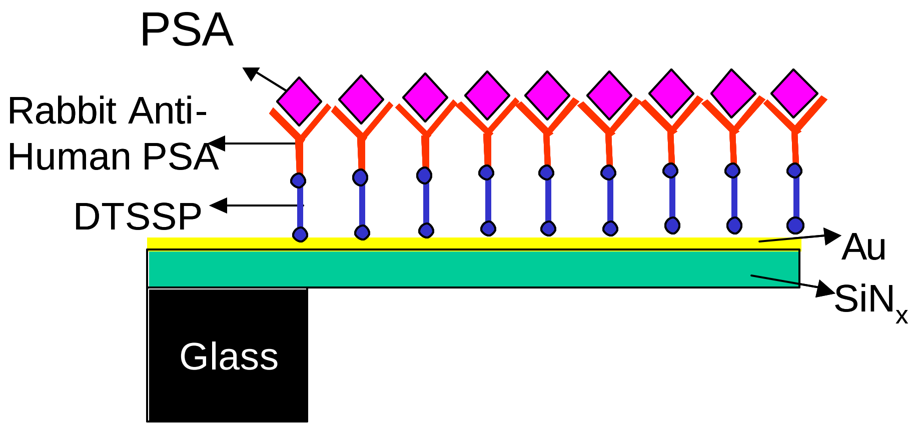
$\Delta S_{conf} = 0$



Moy, V. T., Florin, E-L., & Gaub, H. E. *Science* **266**, 257-259 (1994).

Courtesy: Thomas Thundat, ORNL

Prostate Specific Antigen (PSA) Detection

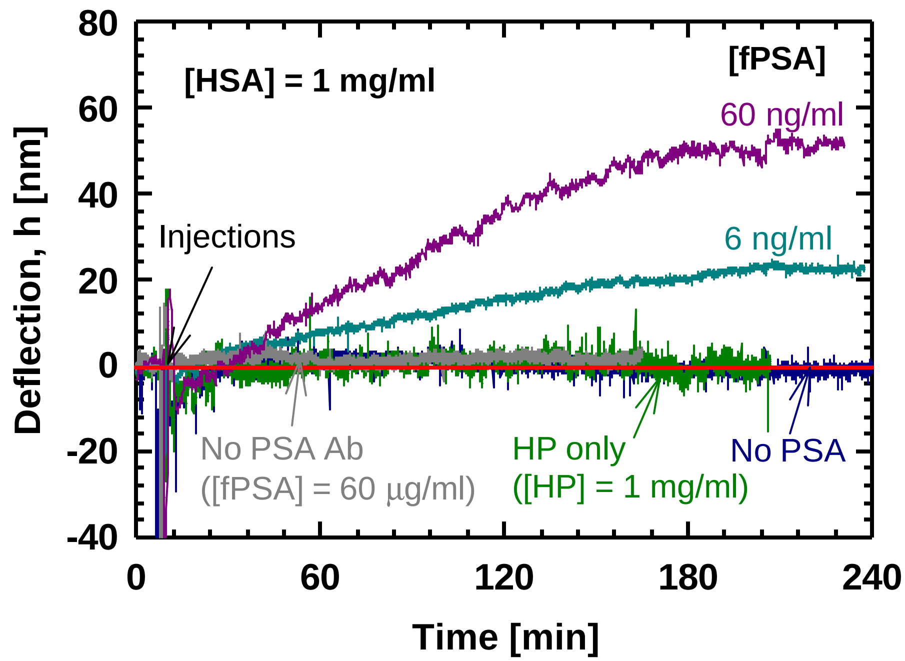


HSA: Human Serum Albumin

HP: Human Plasminogen

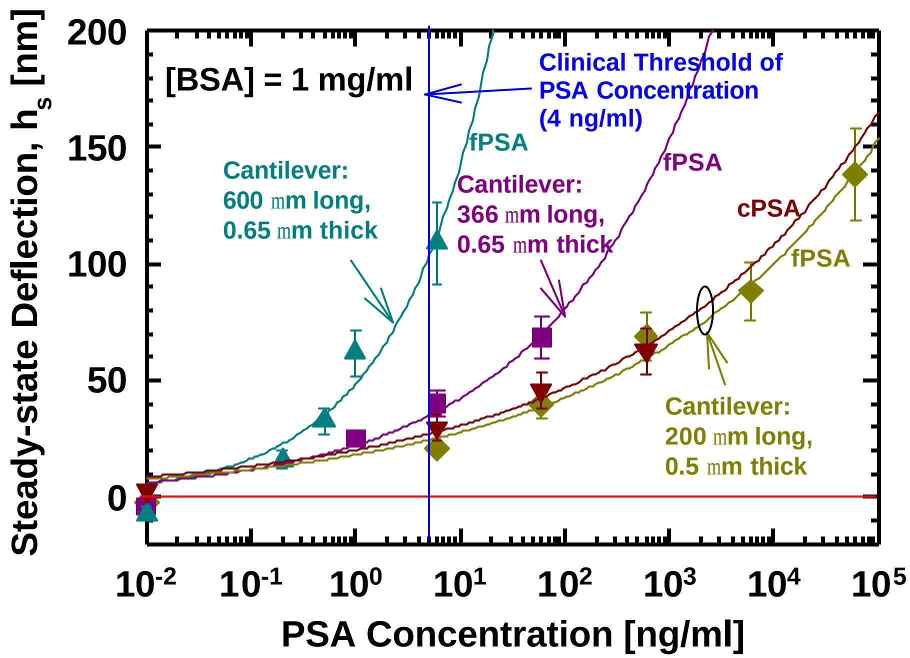
fPSA: free PSA

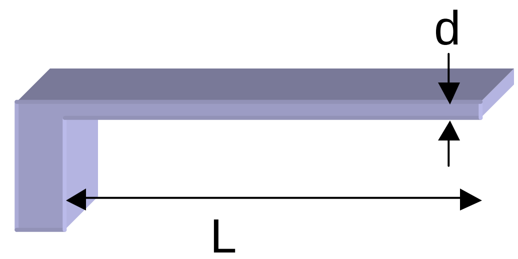
cPSA: complex PSA



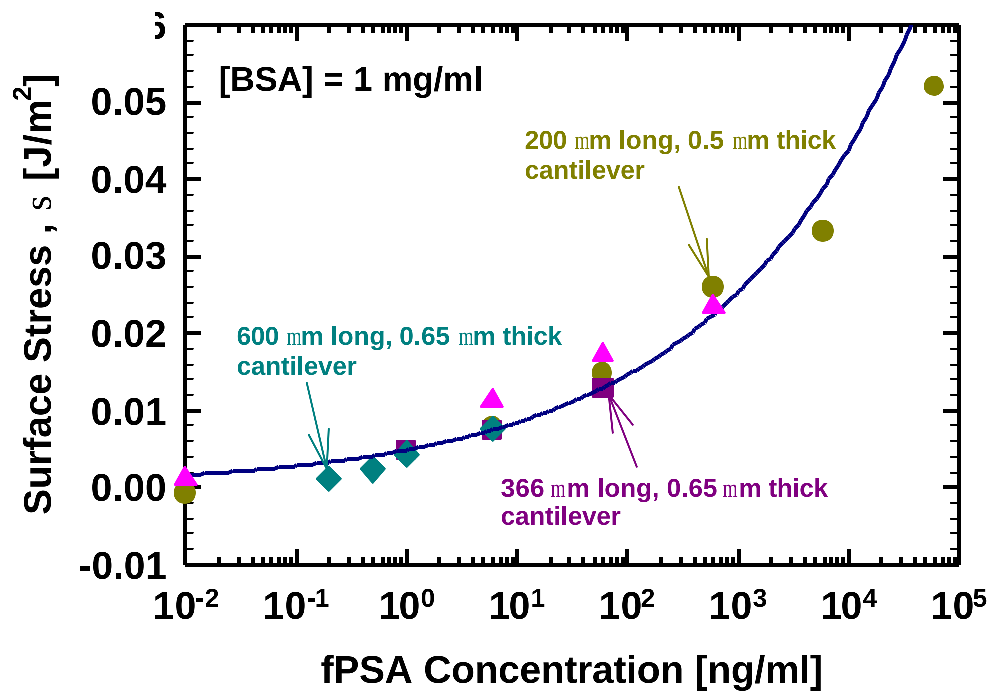
Wu, G. *et al*., "Bioassay of Prostate Specific Antigen (PSA) Using Microcantilevers," *Nature Biotechnology, Vol. 19, pp. 856-860 (2001).*

Nanomechanical Assay of PSA



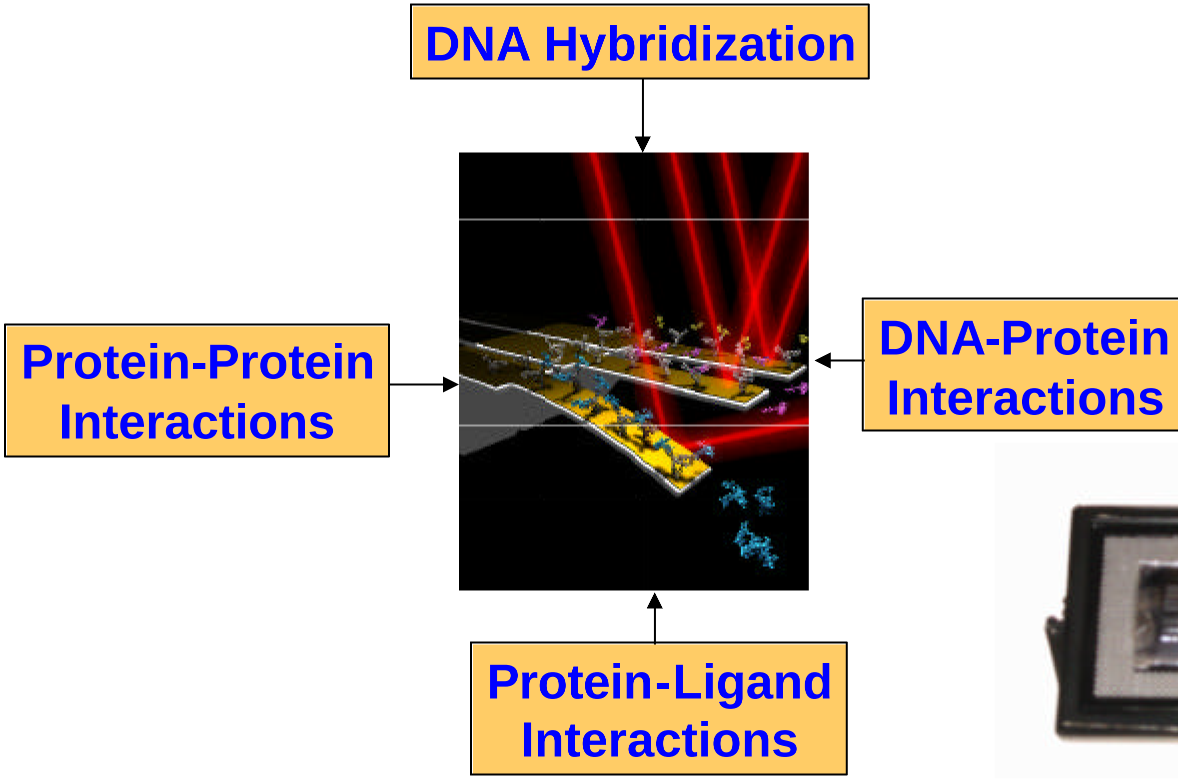


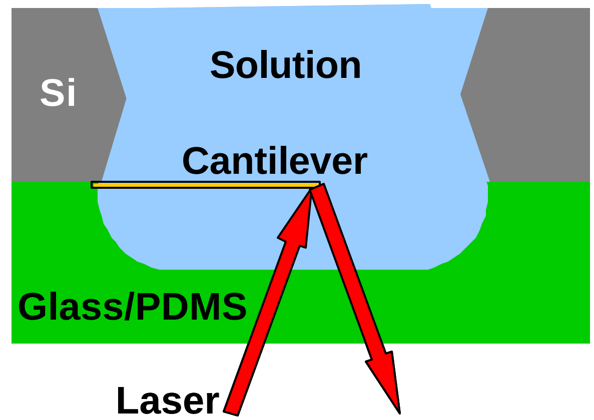
$$h = \frac{s\left(1-n\right)}{E}\left(\frac{L}{d}\right)^2$$

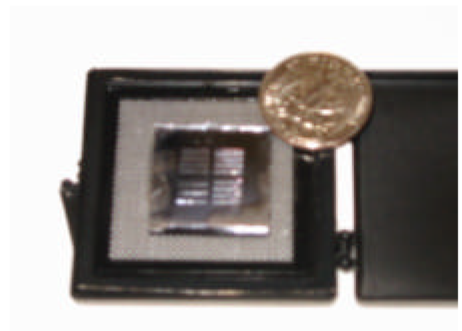


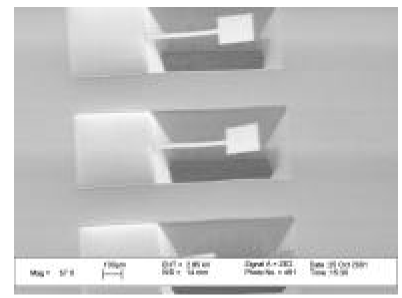
Wu, G. *et al*., "Bioassay of Prostate Specific Antigen (PSA) Using Microcantilevers," *Nature Biotechnology, Vol. 19, pp. 856-860 (2001).*

Common Platform for Label-Free Multiplexed Bioassays

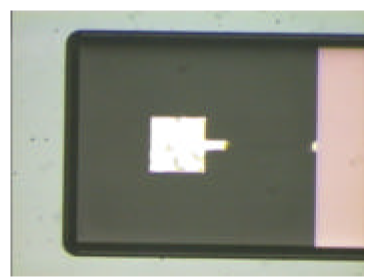




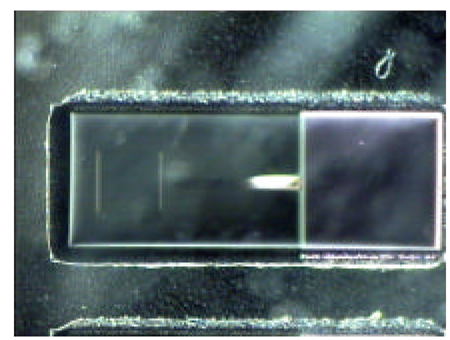




Glass Roof

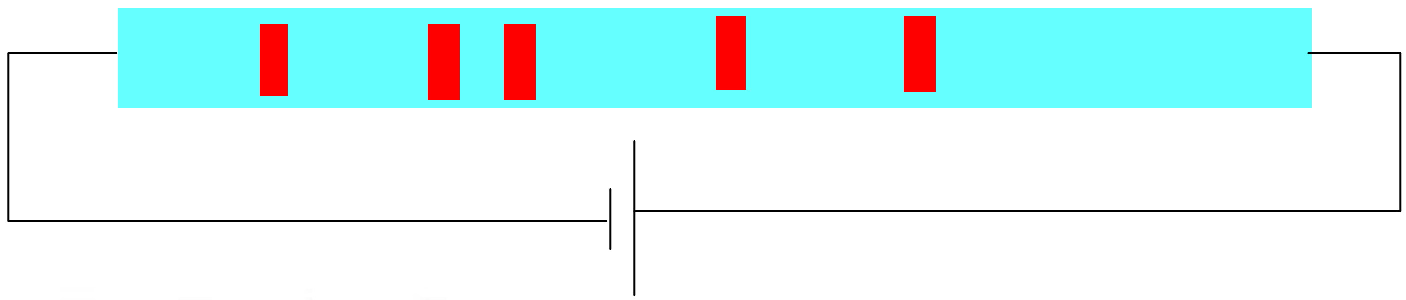


PDMS Roof

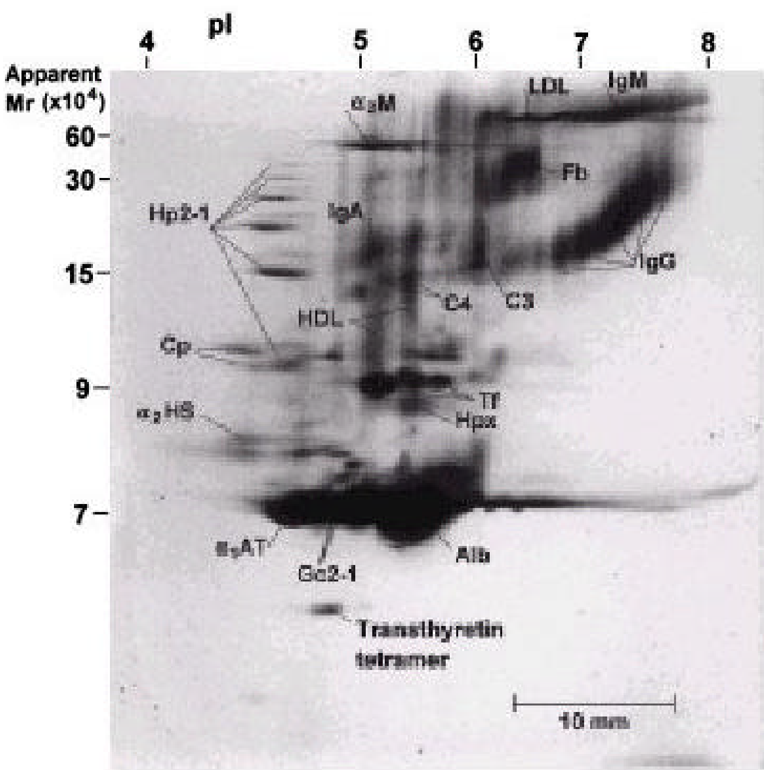


What happens when receptors are not available?

Molecular Separation by Mass and Charge (DNA + Proteins)

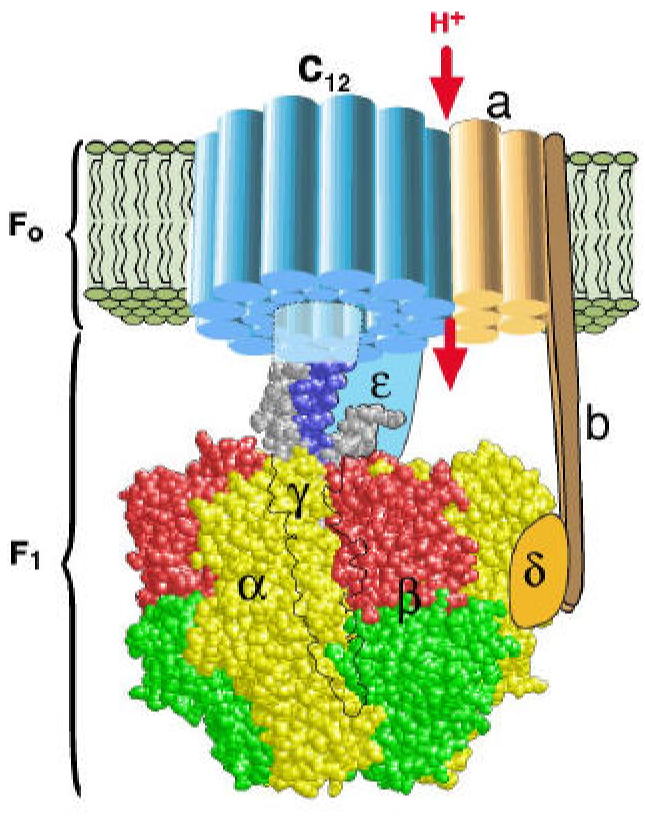


100-1000 V

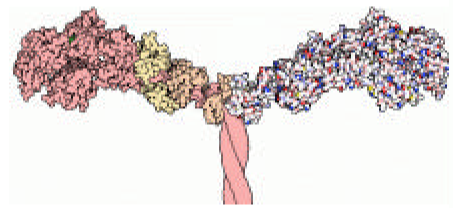


Electric Field ≈ 100-300 V/cm

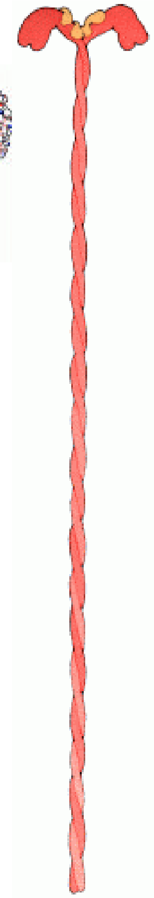
Molecular Motors

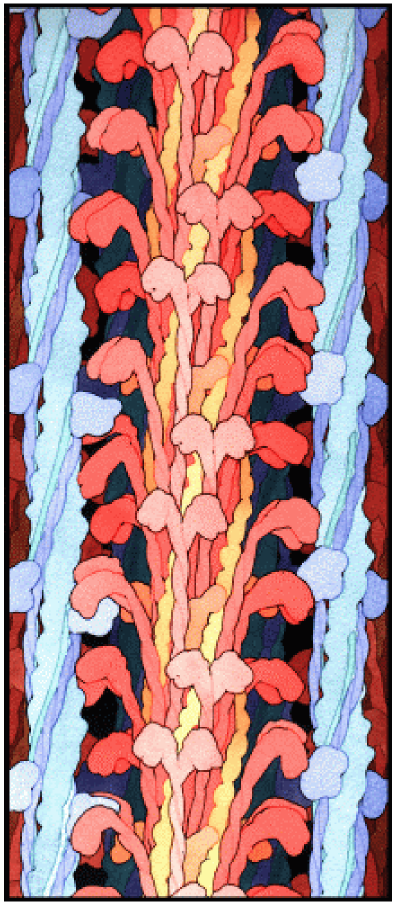


ATP Synthase

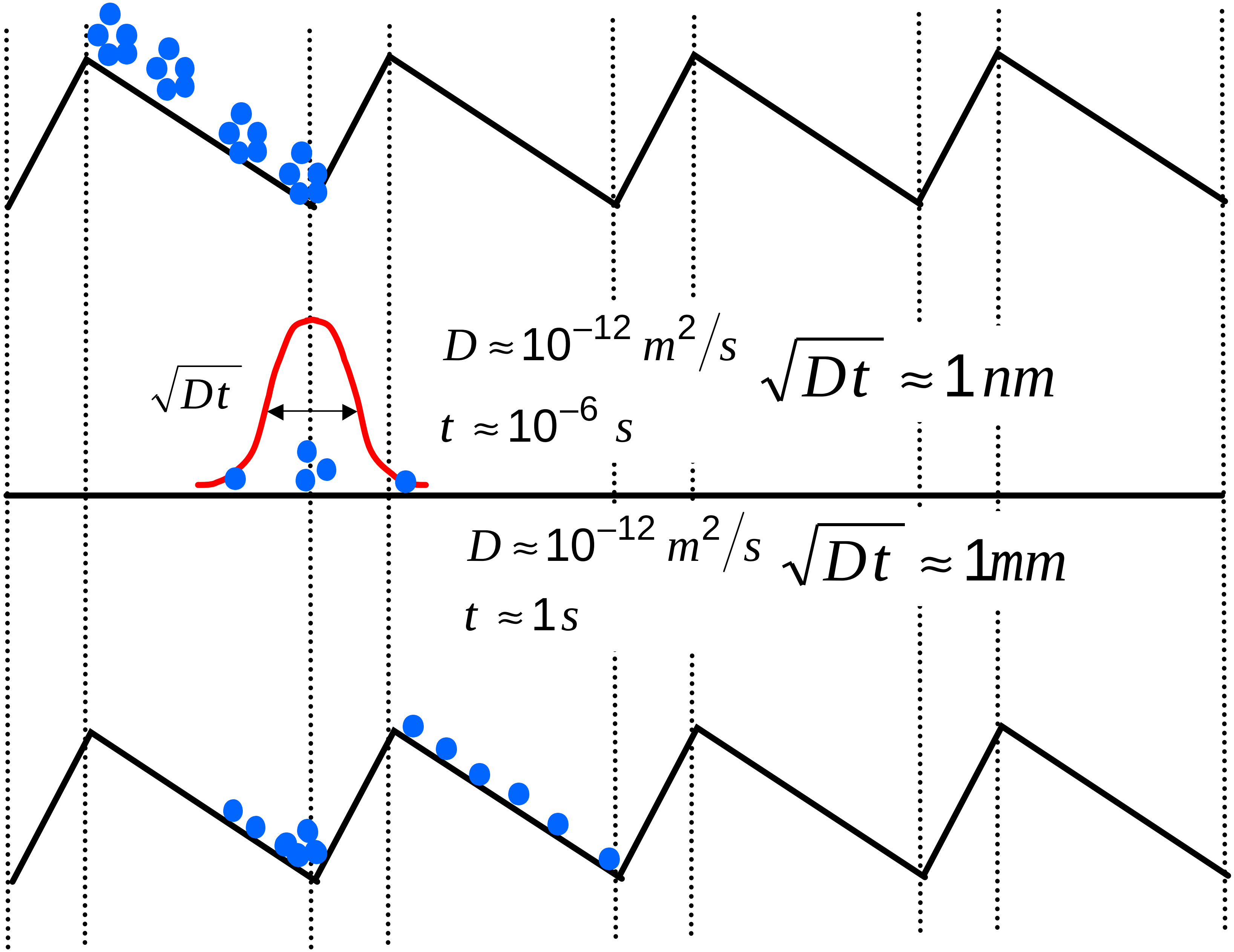


Myosin

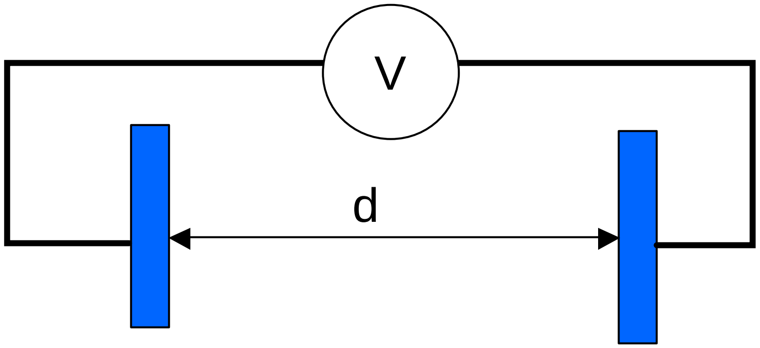




Brownian Ratchets



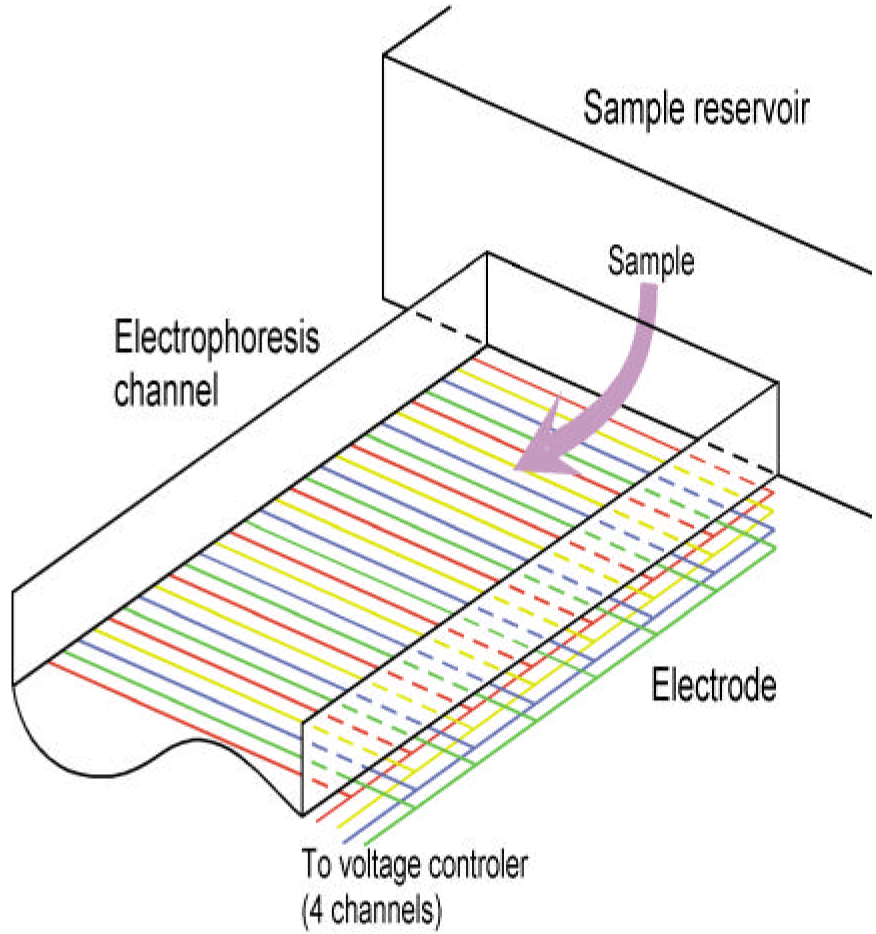
Ratcheting Electrophoresis Microchip: Basic Concept



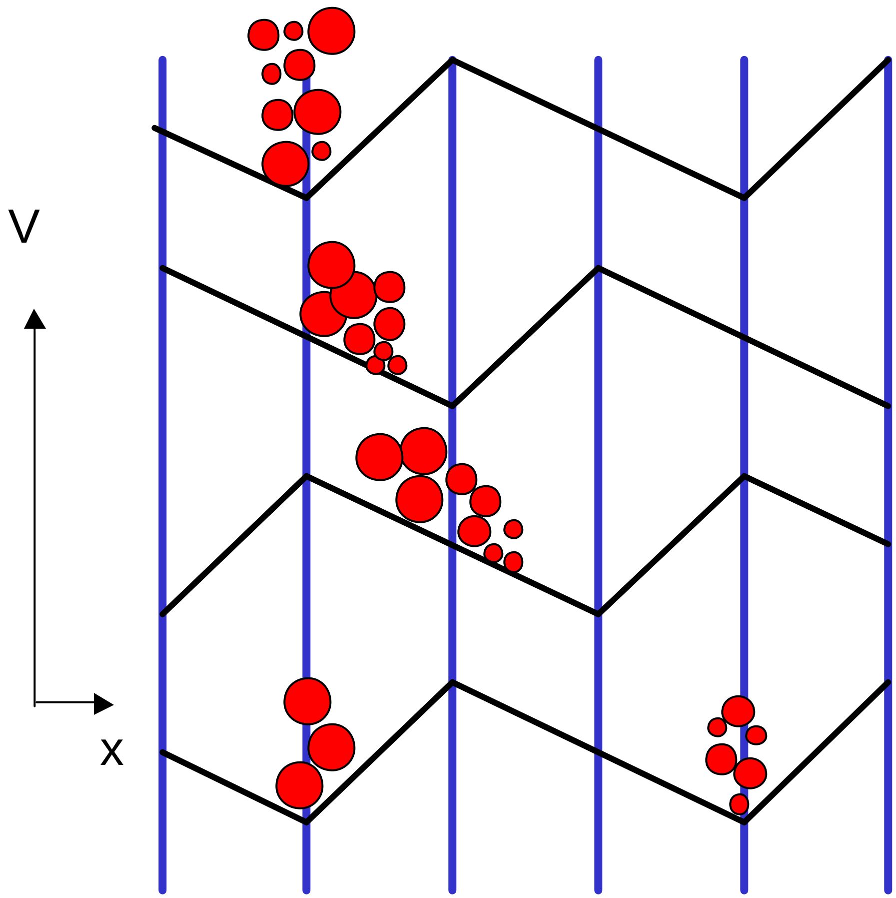
Electrode
Separation, d = 10 μm

Applied Bias, V = 1 V

Electric Field, E = V/d = 1000 V/cm



Basic Mechanism – One Way Motion



Molecules are trapped at the starting line and ready for the electrophoresis process.

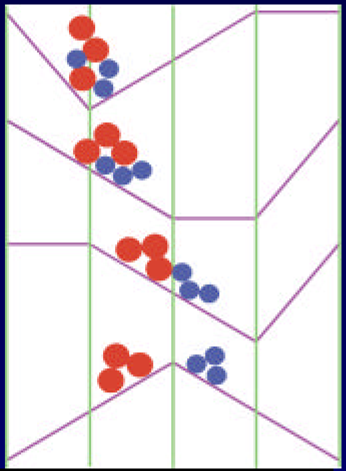
Electrophoresis process. Molecules migrate making a line according to their mobility.

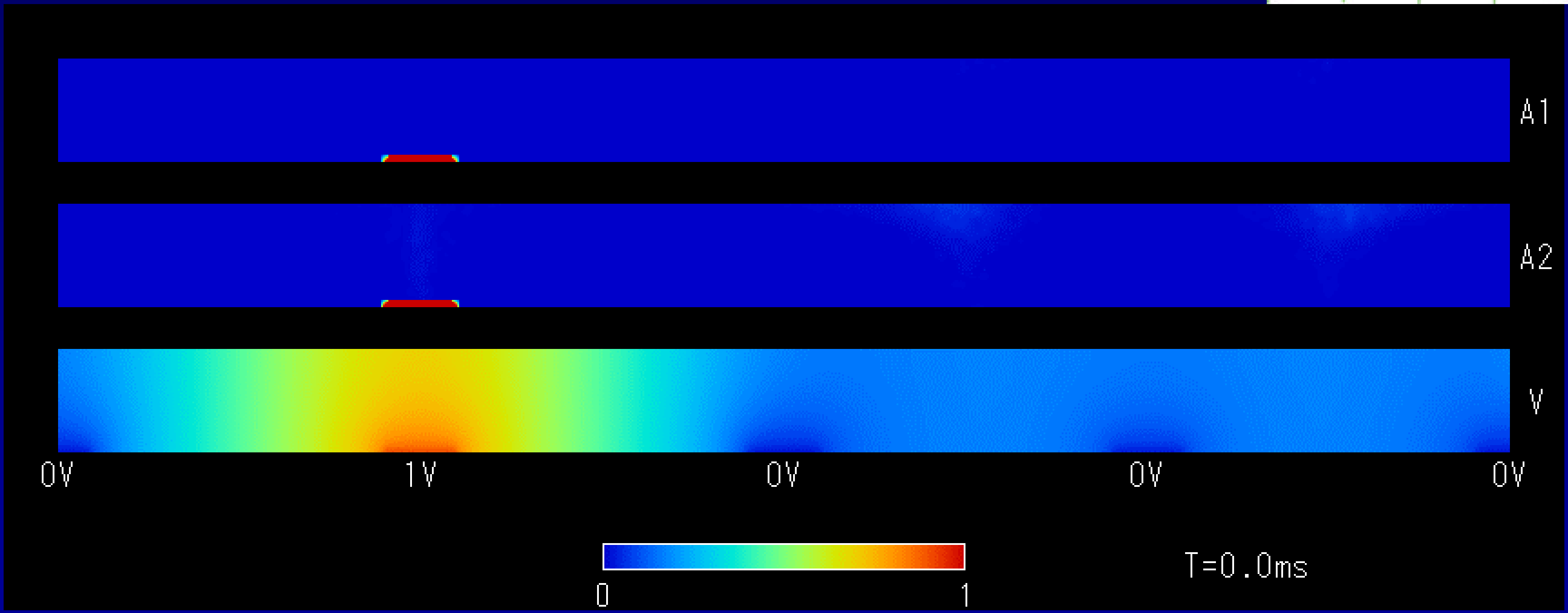
After a threshold time period, the line of molecules is divided by a potential peak and molecules are separated according to their mobility

- Binary separator → Filtering
- No backward motion of molecules

Suffers from thermal noise (mass diffusion)

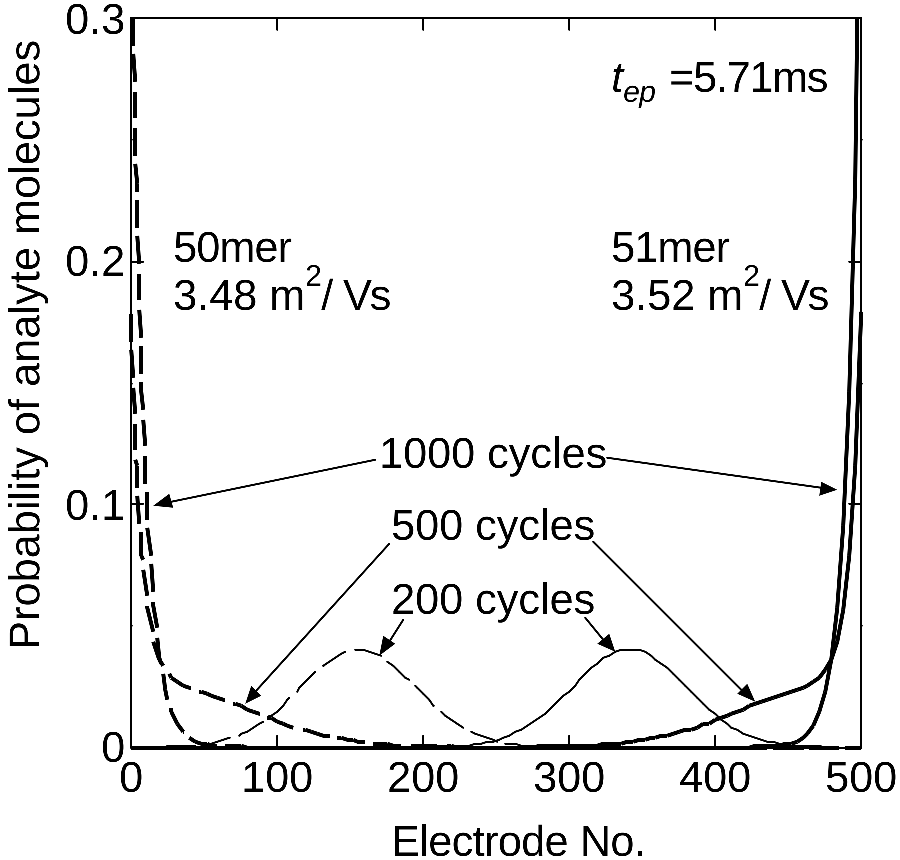
Electrophoresis Separation
(single array system)

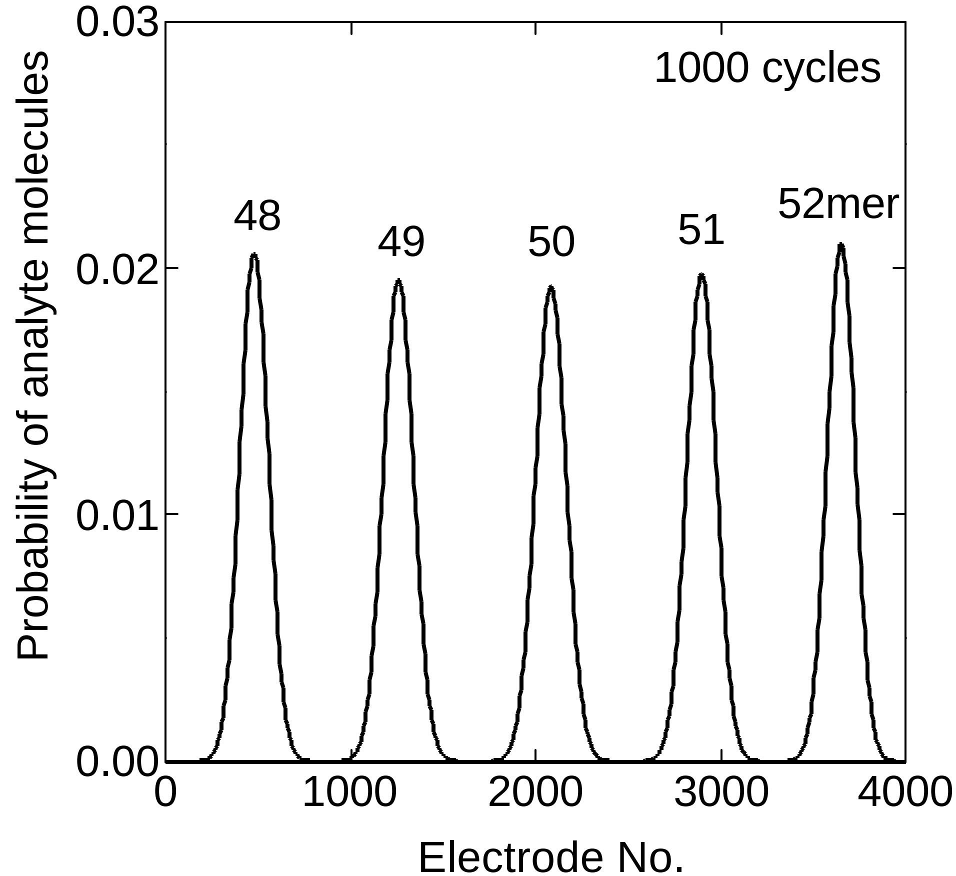




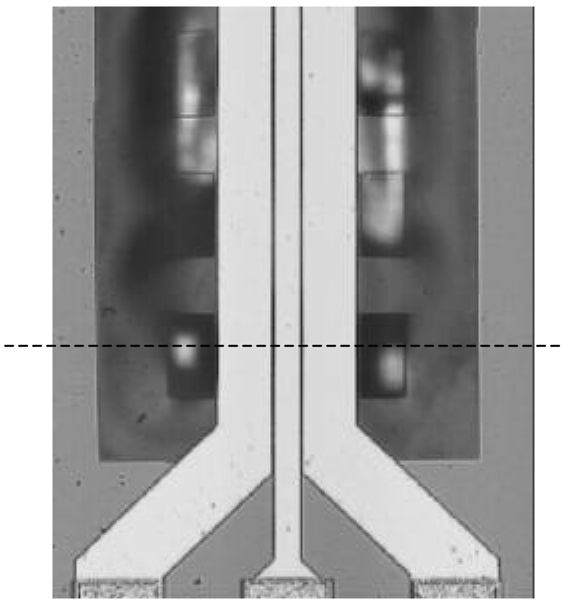
Courtesy: Taku Ohara, Tohuku Univ.

Separation Performance

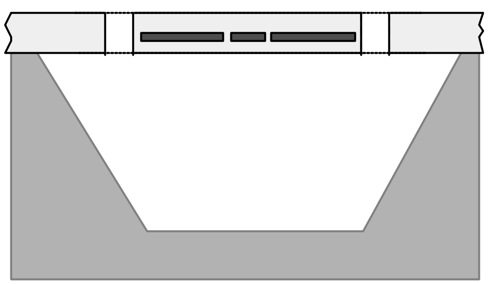




Microwave transmission lines and microfluidic channels?

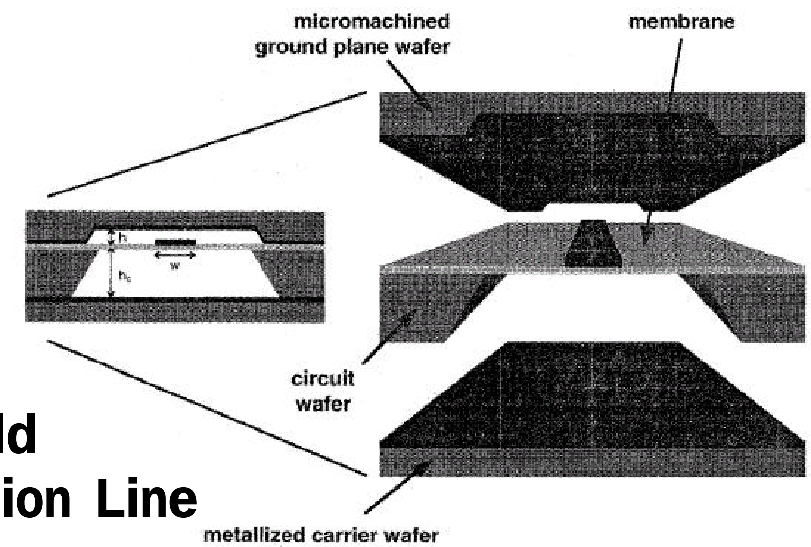


CPW after hybrid micromachining



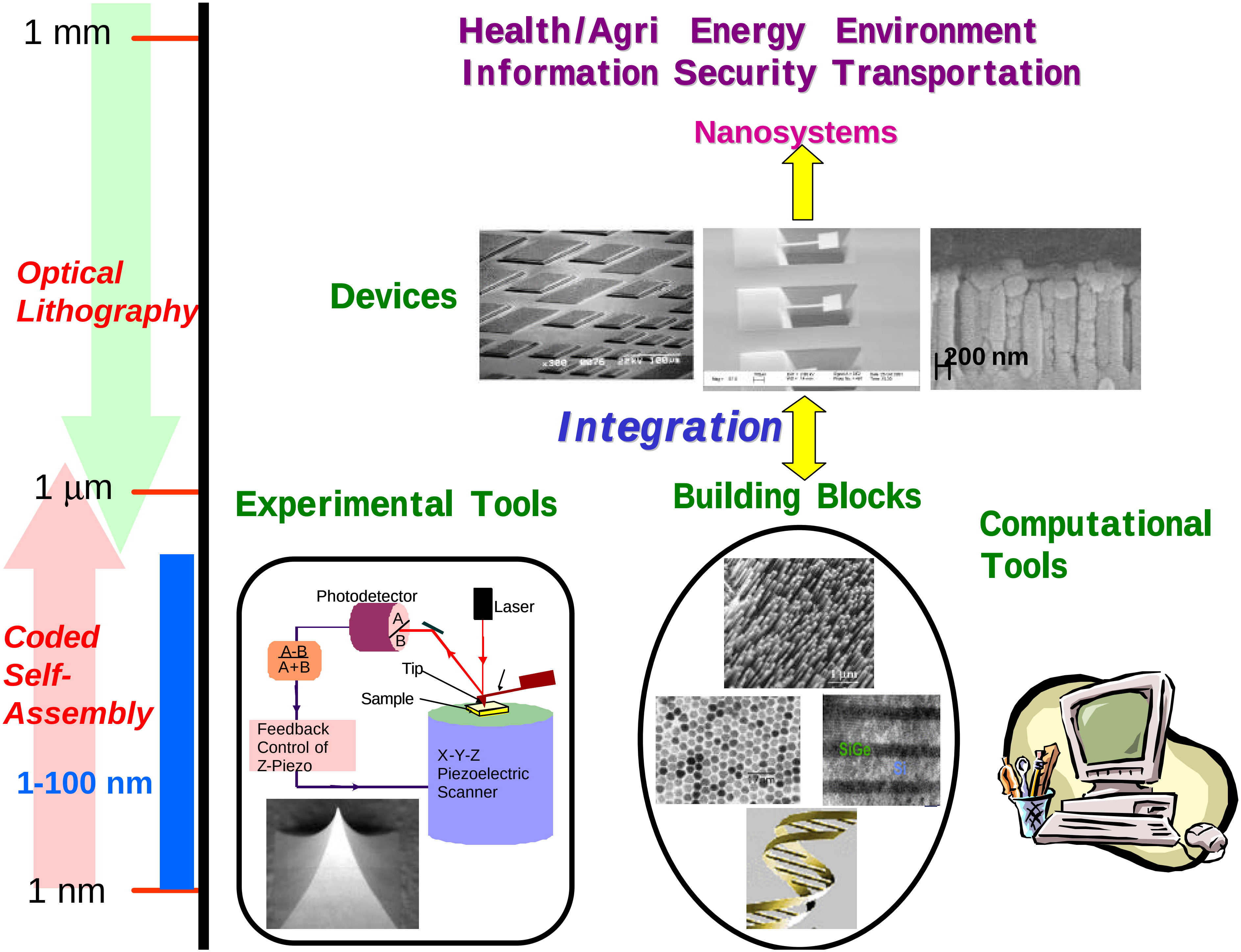
Milanovi', *et al*, IEEE T-MTT , 6/97

- UMich, GWU, …: suspended microwave transmission lines
  - Suspended over air "microchannel"
  - Filling microchannels with fluid samples?
  - Some additional processing or packaging
- Currently investigating potential bio-medical applications of such RF structures
  - ***Anritsu* graciously allowing occasional ANA tests to 120GHz**



Microshield Transmission Line

Robertson, *et al*, IEEE T-MTT , 4/96



1 mm
Optical Lithography
1 µm
Coded Self-Assembly
1-100 nm
1 nm
Health/Agri Energy Environment
Information Security Transportation
Nanosystems
Devices
200 nm
Integration
Experimental Tools
Photodetector
Laser
A
B
A-B
A+B
Tip
Sample
Feedback Control of Z-Piezo
X-Y-Z Piezoelectric Scanner
Building Blocks
SiGe
Si
Computational Tools

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- Andy Miner (PhD, 5/02)
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- Michael Chapp
- Woo Chul Kim

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- Dan Dedirck
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