Nanotechnology Applications for Environmental Sensors: *Integrated Devices for Real-Time Analyses*

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Arizona State University

Dec. 2004

Need of Environmental Sensors

The Washington Post

High Lead Levels Found in Water At 9 D.C. Schools

District to Issue Warning on Lead

Health Advisory on Water to Target Pregnant Women, Small Children

Youngsters, Fetuses Are Most Vulnerable

Studies Find IQ, Socialization Problems

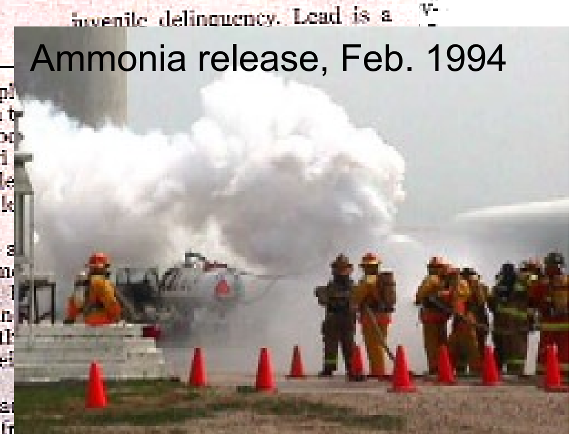
By Avram Goldstein
Washington Post Staff Writer

City health officials who pl… to issue an alert about lead in t… water are most concerned abo… children younger than 6 and … tuses—those most susceptible … permanent damage from le… poisoning.

Rapidly growing bodies … unborn children are far m… likely to absorb lead that … been swallowed or inhaled, an… poses a grave threat to th… long-term health and well-bei… experts say.

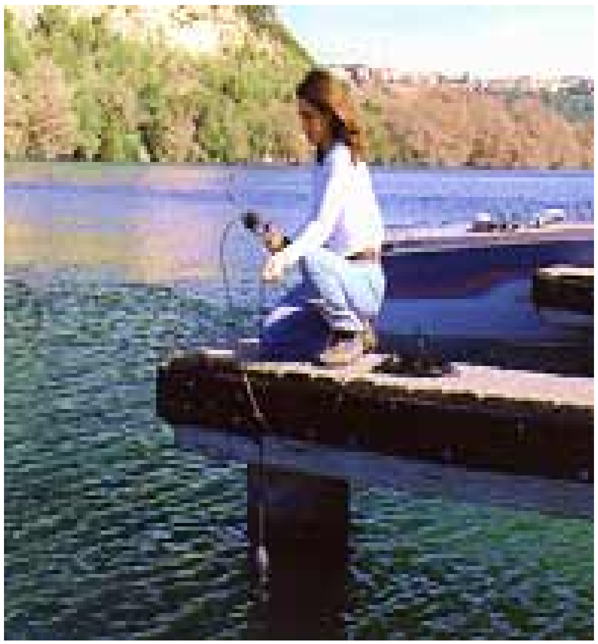
Children who ingest lea… usually in the form of dust … deteriorating lead-based paint or …

WASA official Jodye Levy Russell takes a water sample from a faucet at Leckie Elementary in Southwest during a testing demonstration earlier this month.



Ammonia release, Feb. 1994

Water Quality Monitoring



Current
Manual test

Near Term
Wireless system
With single probe

Future
Wireless system with
PWB array probes

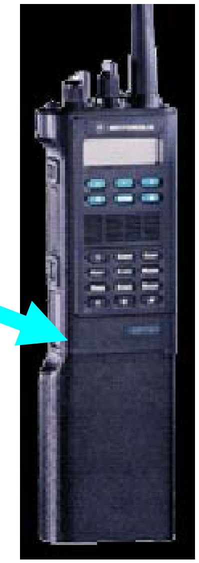
Air Quality Monitoring

Current

Only select personnel (Hazmat) typically carry portable equipment

Near Term

Provide wireless connectivity of portable equipment to communicate to incident commander

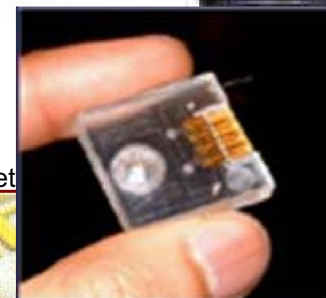


Future

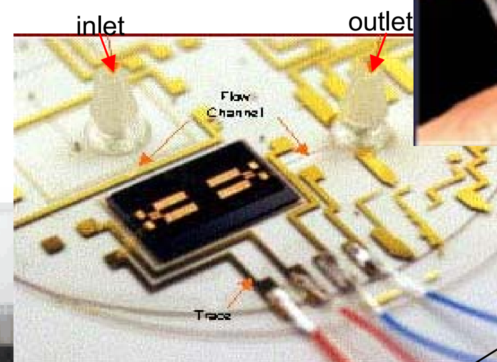
Essential monitoring is integrated into communications equipment

Need:
Miniaturization
& Integration

Signal Processing
& Transmission

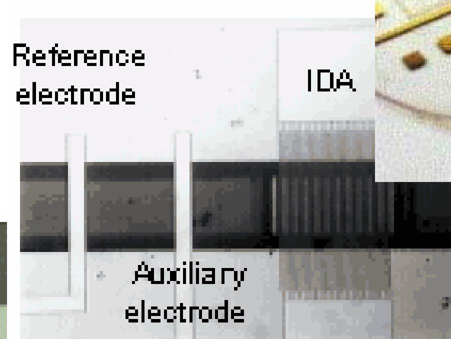


Sample Delivery



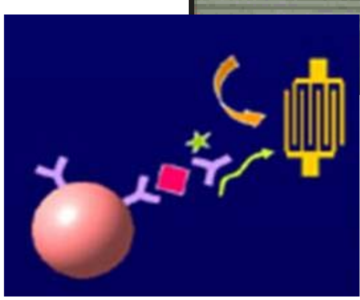
~cm

Sensing
Element
Array



~mm

~µm



~nm

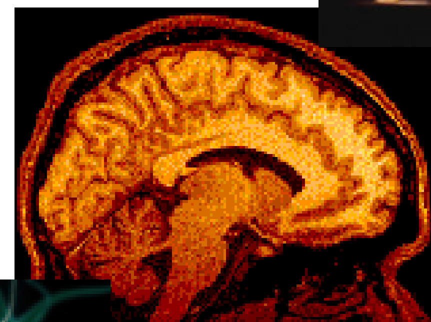
An Integrated Sensor

- **Sample Delivery**
- **Sensing Elements**
- **Signal Processing & Transmission**

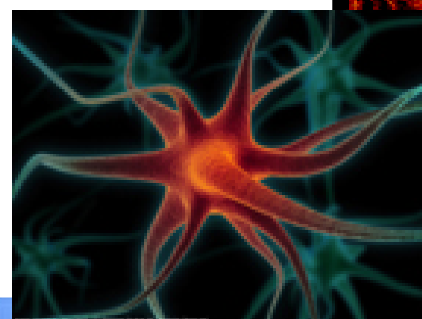
Emulating Nature…

Data processing, Action,
(cm-m)

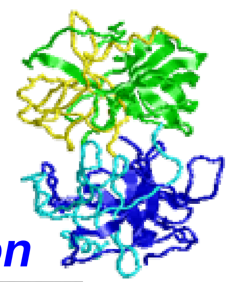
Brain (mm-cm)

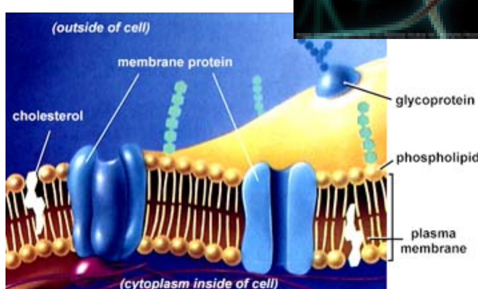


Neurons (um)

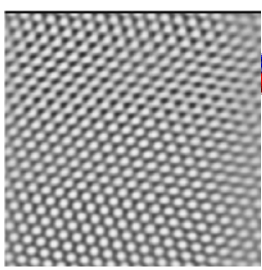


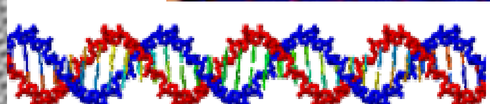
Proteins (~ 5 nm)
DNA (~ 2nm wide)
Lipids (~ 1 nm)





Atoms
of carbon





Spacing ~ 1.5 Å

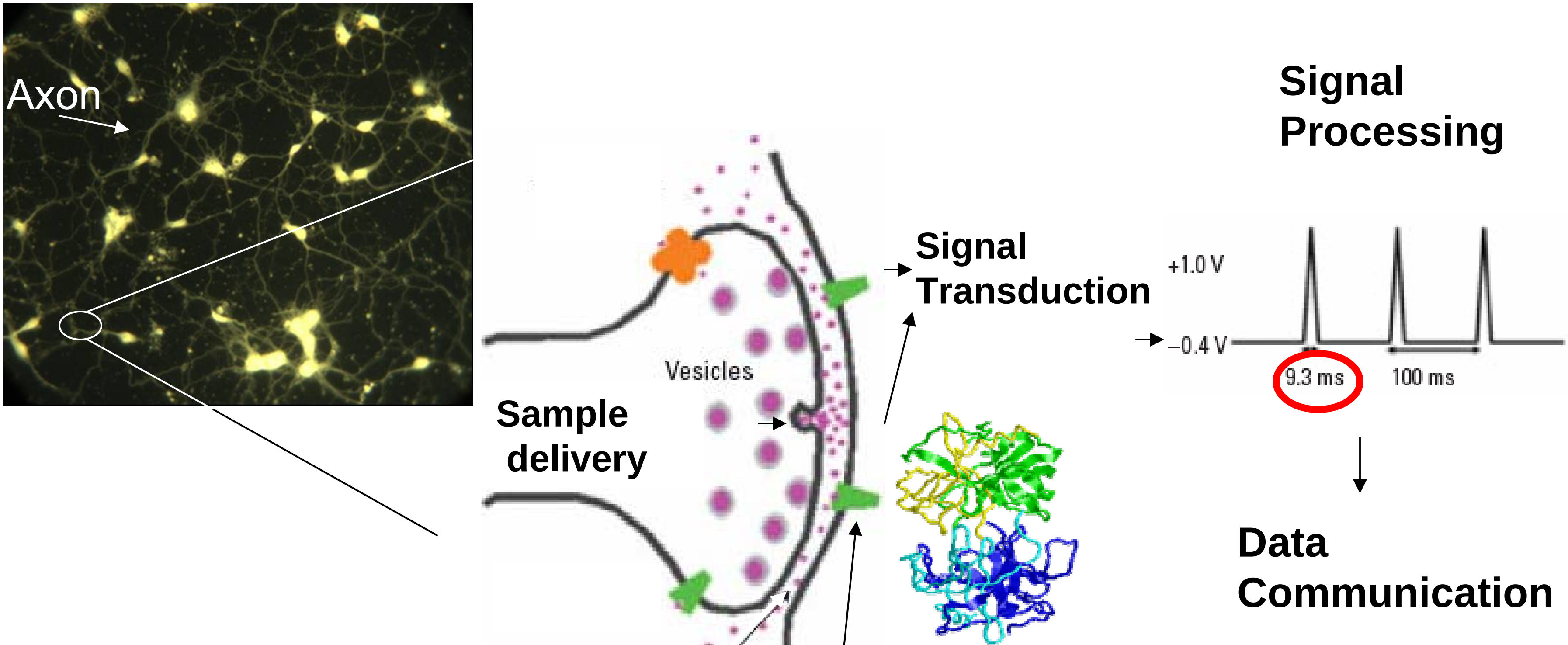
macro

micro

nano

Emulating Nature: Neuronal synapses…

Perfect feed-back system to imitate…



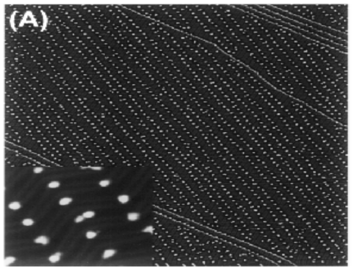
Recognition elements (specific sensing molecules)

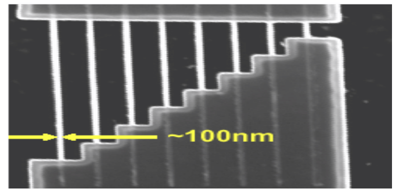
- 100nm gap
- Sub second response
- High specificity
- Response to nM concentrations

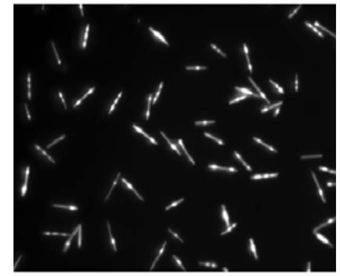
B.J. Venton, R.M. Wightman, Anal. Chem, 2003, **4 1 4 A**

What role does ‘NANO’ play?

NANO-Solution ?



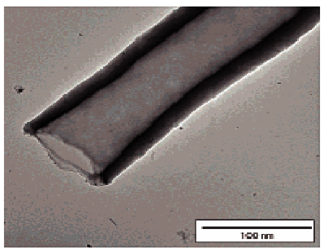




Particle

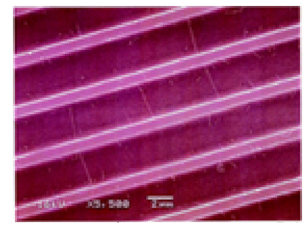
Resonator

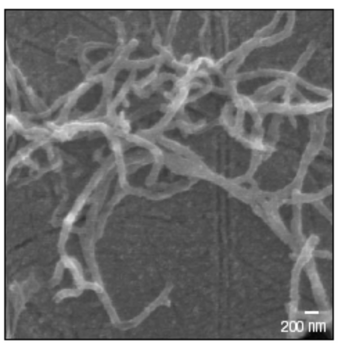
Rod



Peptide Tube

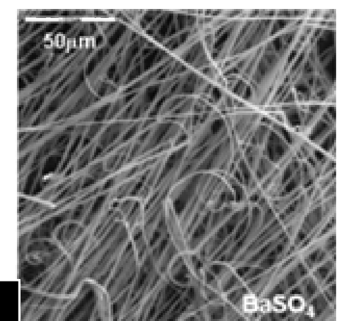
Carbon Tube





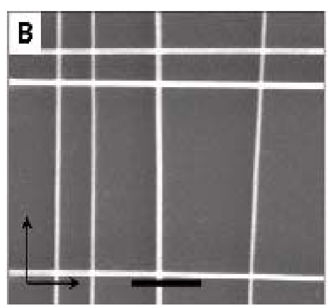
Fibers

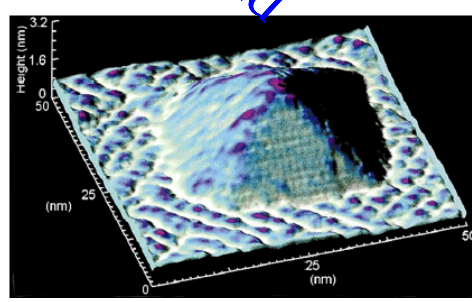
Belt



Wire

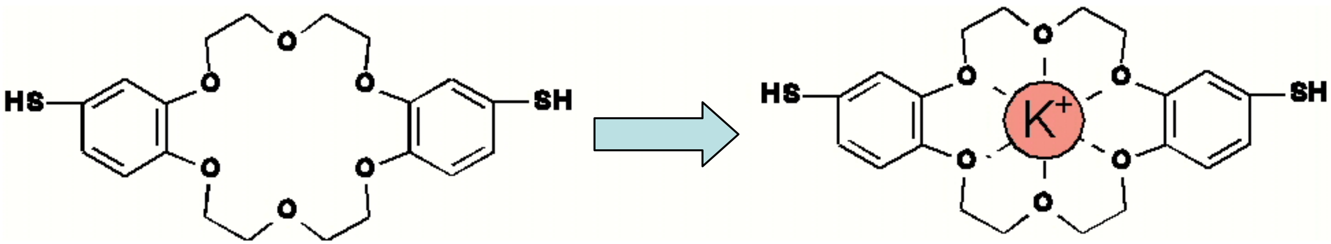
Pyramid





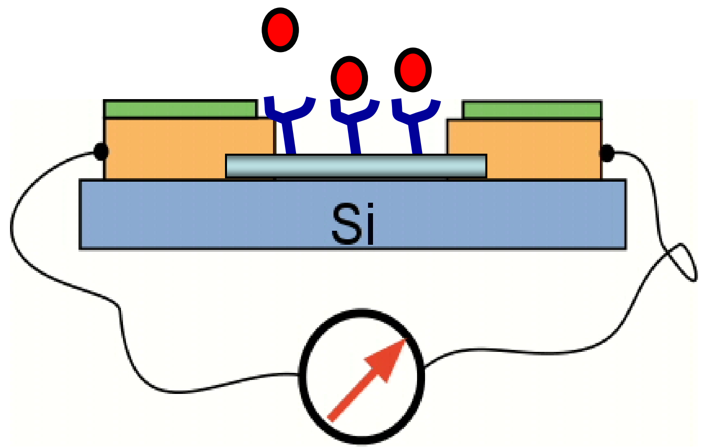
Signal Transduction

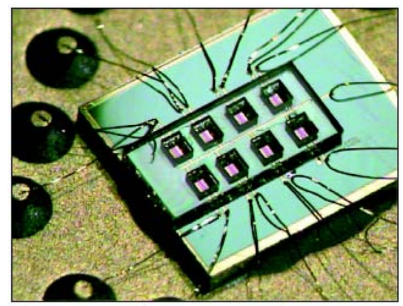
- Convert a Chemical Binding Event into a Readable Signal

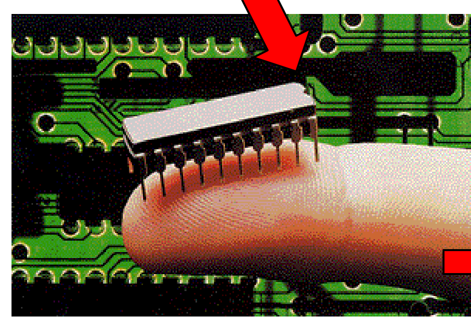


- Optical (Trogler/Gawley/Lavine/Anderson…)
- Electrochemical (Wang/Sadik/…)
- Mechanical (Shih/…)
- Electrical (Kan/Mitra/Subramanian/Tao)

Electrical Detection – Reading chemical information electronically





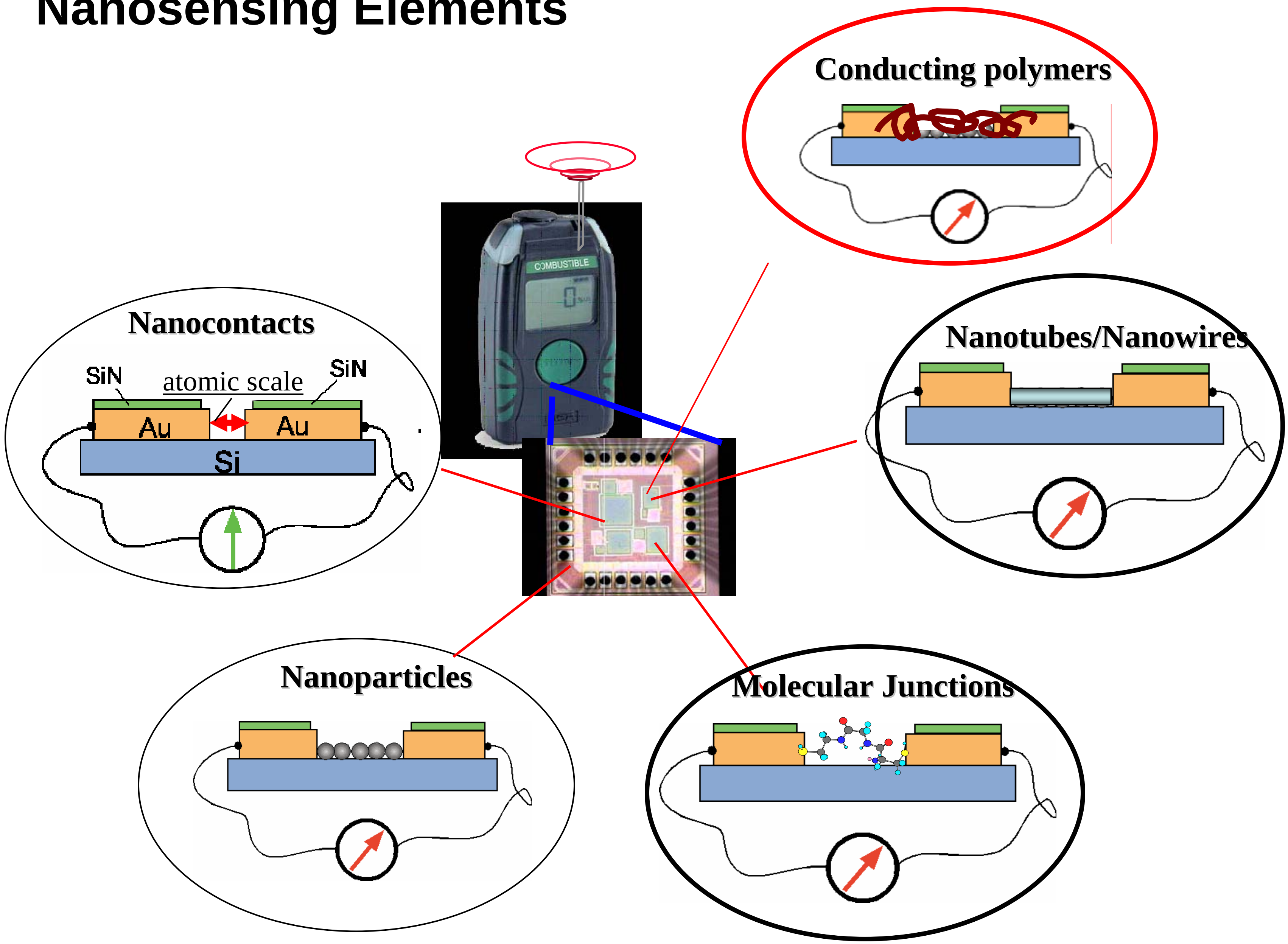


•High degree of integration
-for a miniaturized device for simultaneous detection of different species

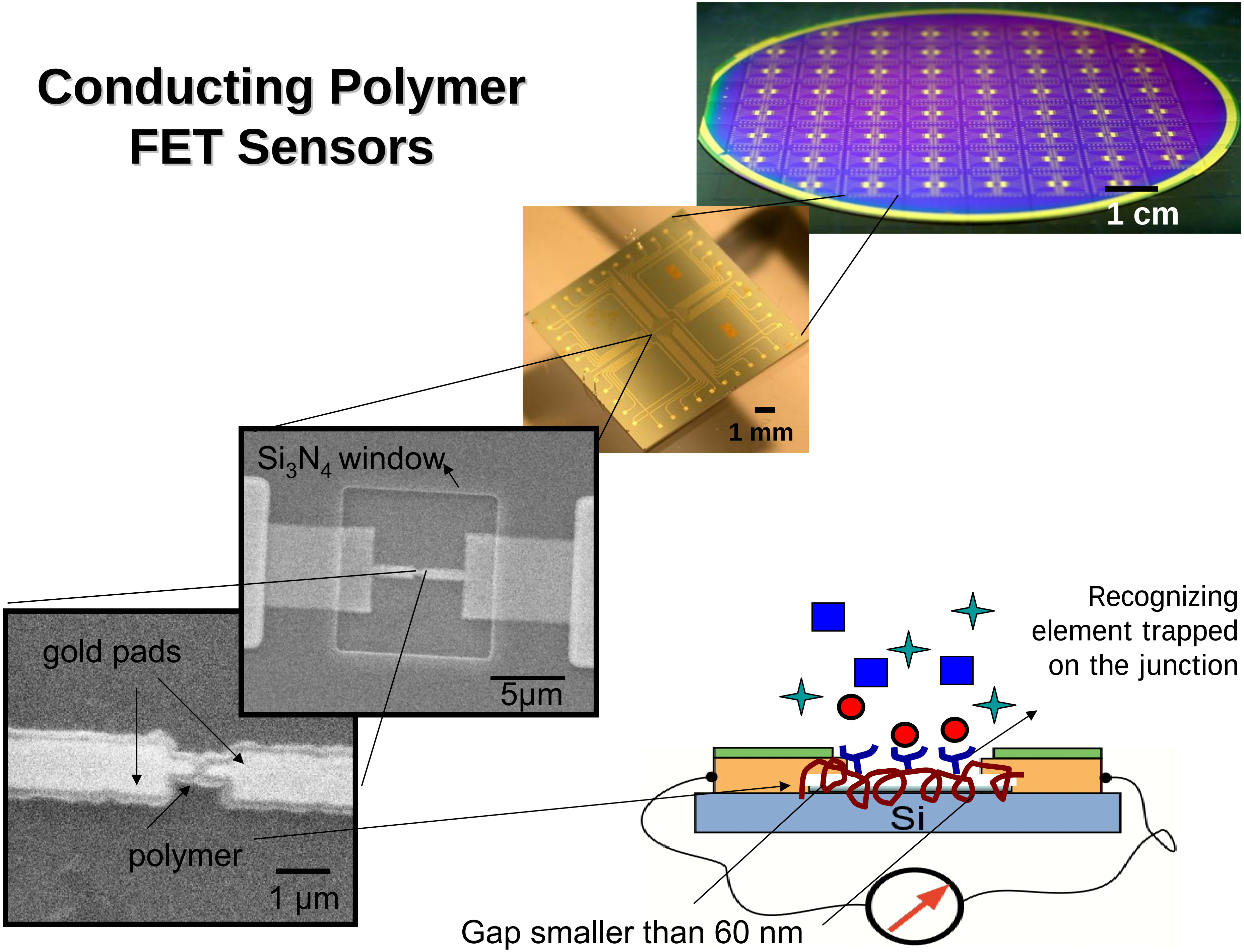
• **Easy to process/display/transmit the data**
  – needed for a fully automated device

• Compatible with microelectronics
  – taking advantage of existing microtechnology

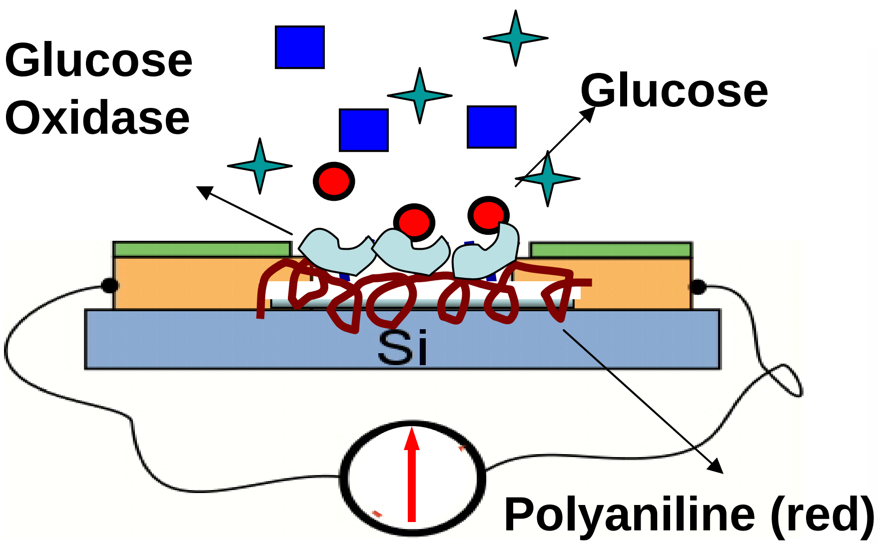
Arrays of Electrically Wired Nanosensing Elements



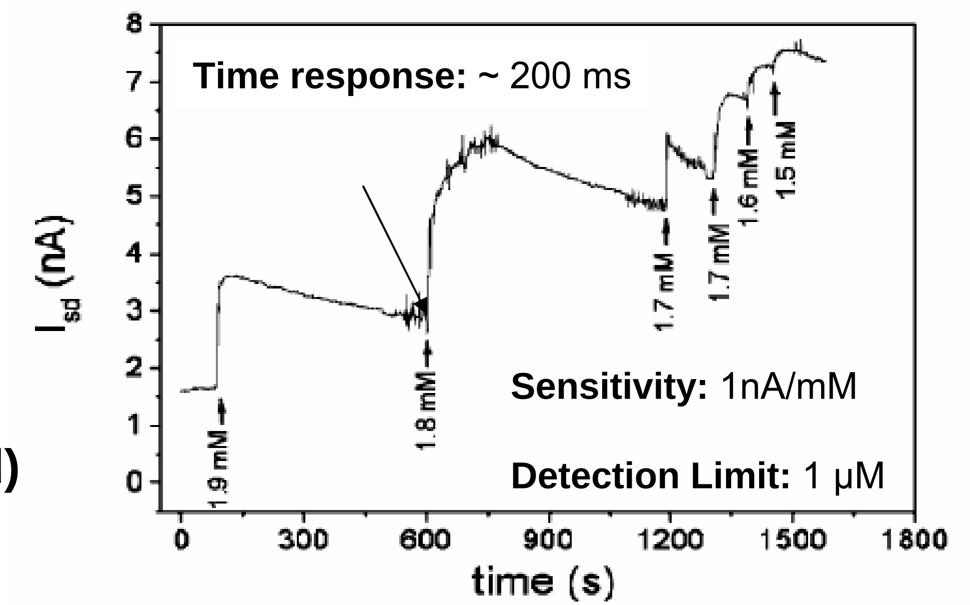
Conducting Polymer FET Sensors



Glucose Sensor



E. Forzani, H. Zhang, L. Nagahara, I. Amlani, R. Tsui, and N.J. Tao *Nano Letters 4 ,9 2004*



✓300 times faster

✓100 times more sensitive

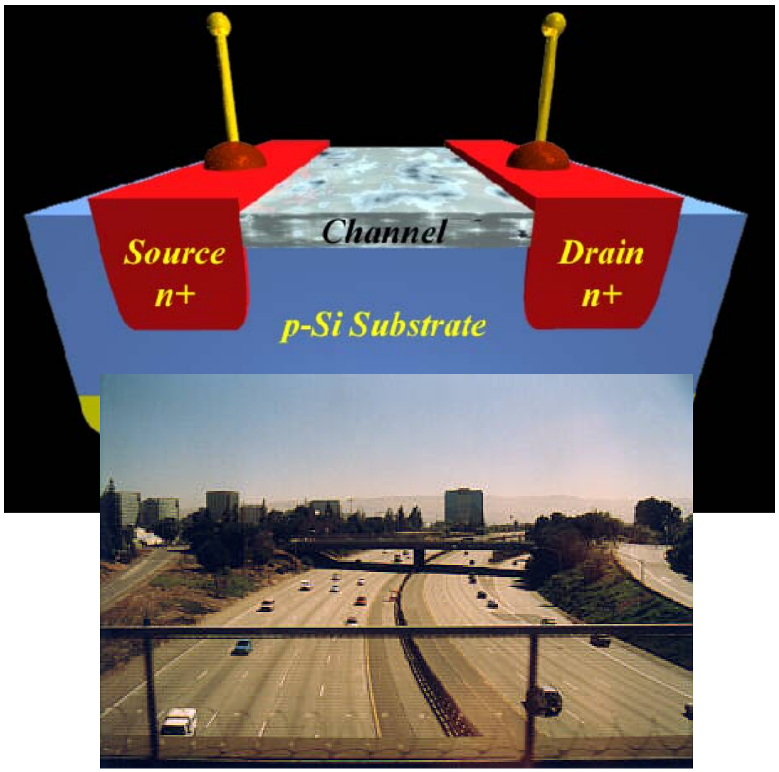
than similar sensors on 20 μm gap.

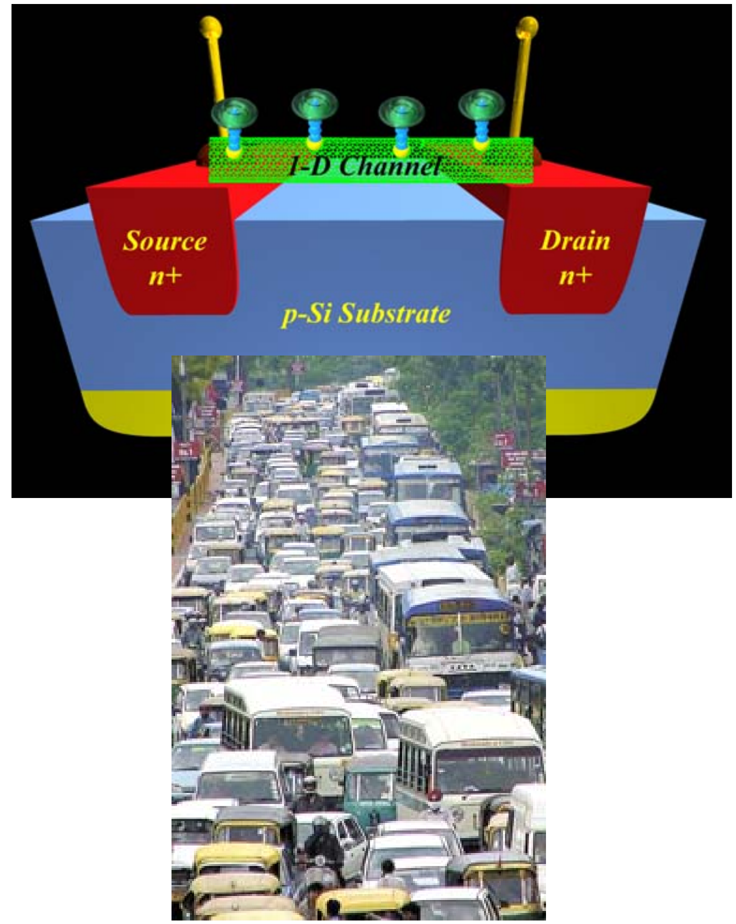
Why nanosensors are better than microsensors ?

Gap smaller than 60 nm

Gap ~ (20 x 900) μm

<u>The clue:</u> **2D sensors vs 1D sensors**





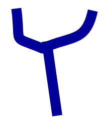
In a conventional FET, conduction through the channel region is two dimensional (i.e., many pathways).

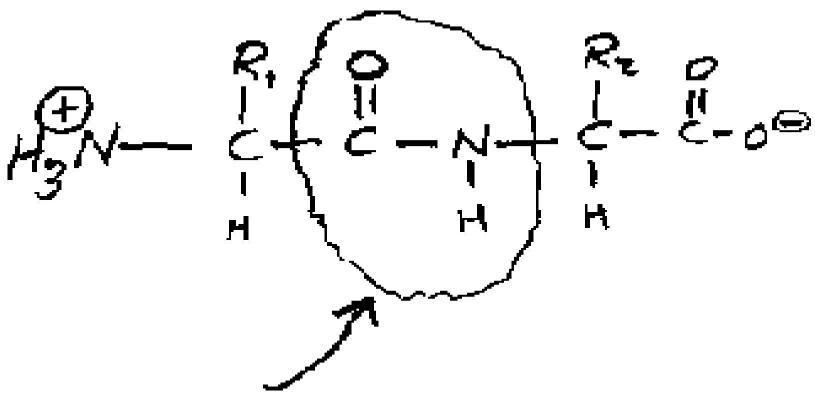
Narrowing the channel to one dimension, detection sensitivity is enhanced.

ChemFET (Kan/Mitra/Subramanian)

Is it necessary using real biological recognizing elements for environmental applications?

Peptides

Molecular Probe:  = peptides



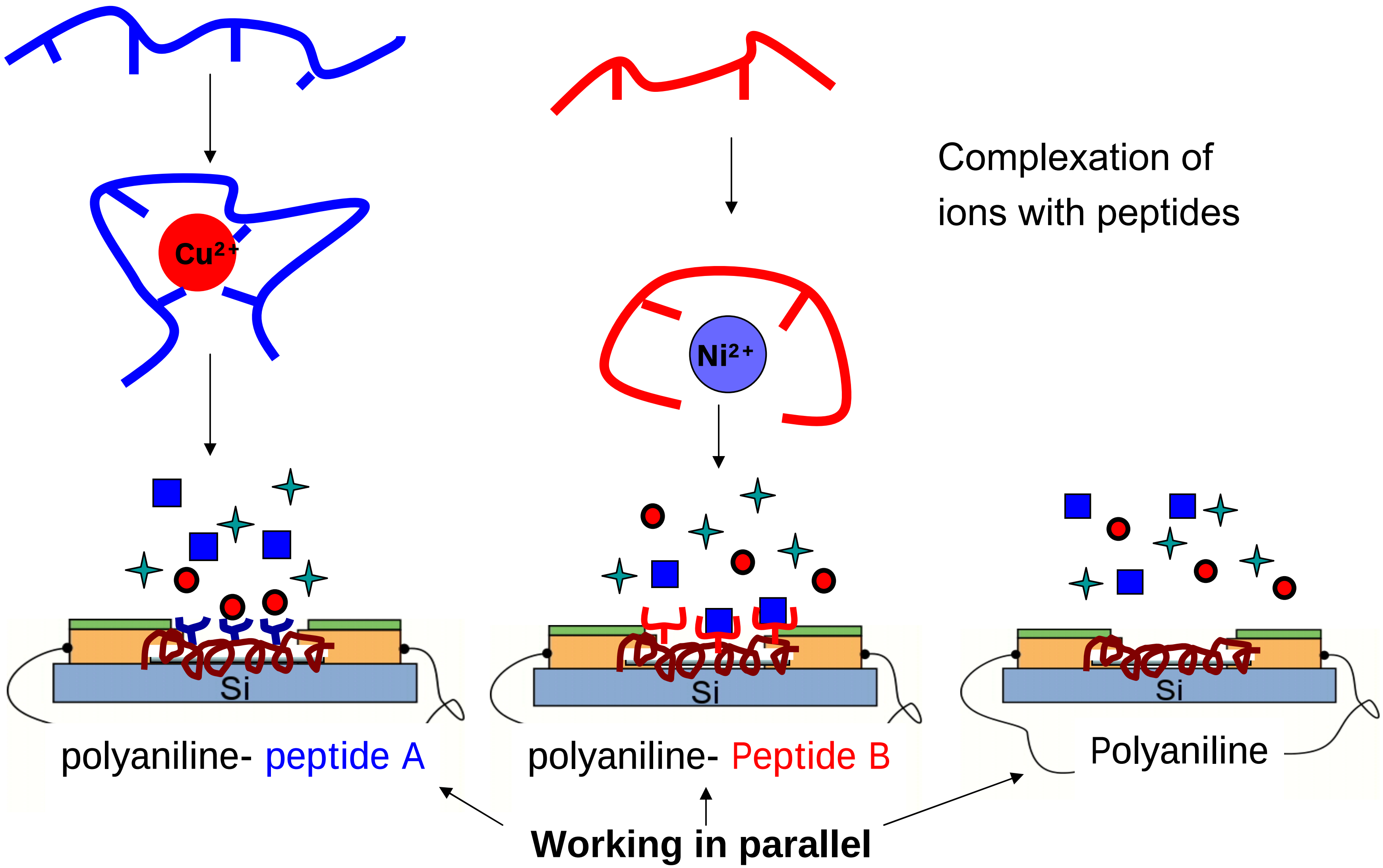
The Peptide Bond

20 amino acids:

Gly	Ala
Val	Leu
Ile	Pro
Pen	tyros
Tyr	Ser
Thr	Met
Cys	His
Lys	Arg
Asp	Glu
Apn	Gln

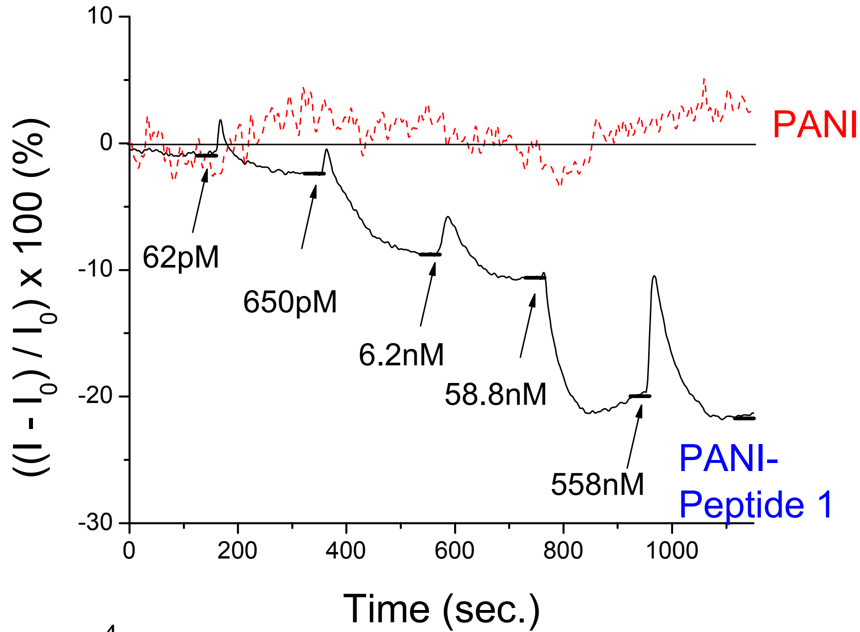
- ✓ Building blocks of protein – Proteins in Nature as guidance
- ✓ Unlimited Choices (4 amino acids ->20x20x20x20=160,000!)
- ✓ Powerful Combinatorial Chemistry

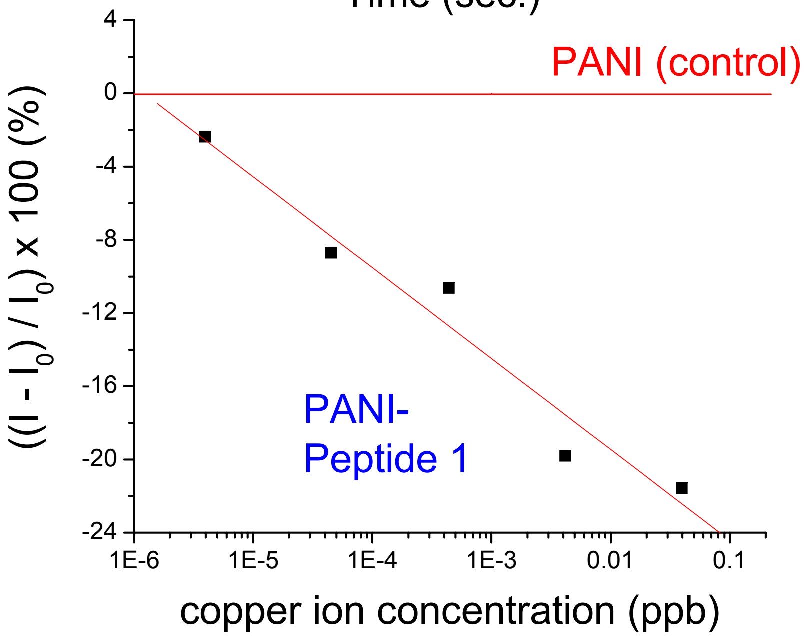
Copper and nickel ion sensors



Copper and nickel ion sensors

Cu^{2+} detection on polymer nanojuctions





- Changes physical-chemical structure and electrical properties → Real time detection
- D.L.(Cu^{2+}): 4 ppt, D.L.(Ni^{2+}): 22.5 ppt
- Reusable device (6 times) for metal ion detection
- Drinking water analysis (Tempe): (0.34 ± 0.03) ppm. Result in agreement with AAS.

Comparison with 100 μm gap FET (polycarbazole):

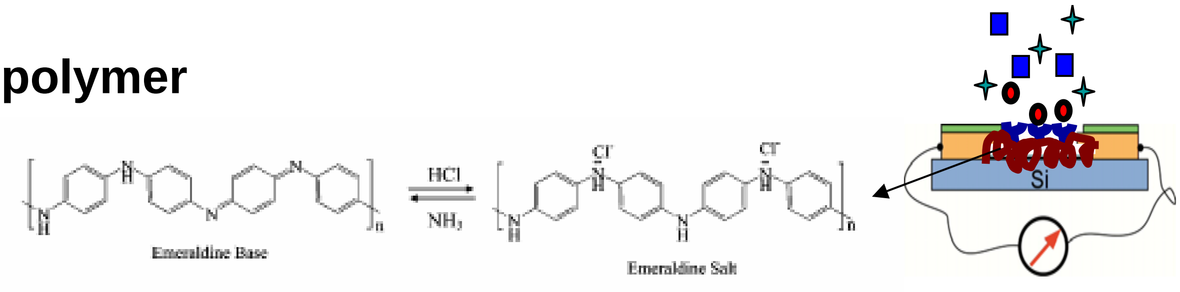
✓ 4 x 10^4 times more sensitive

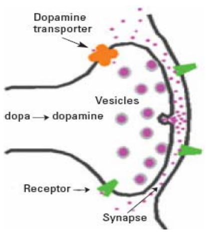
✓500 times faster

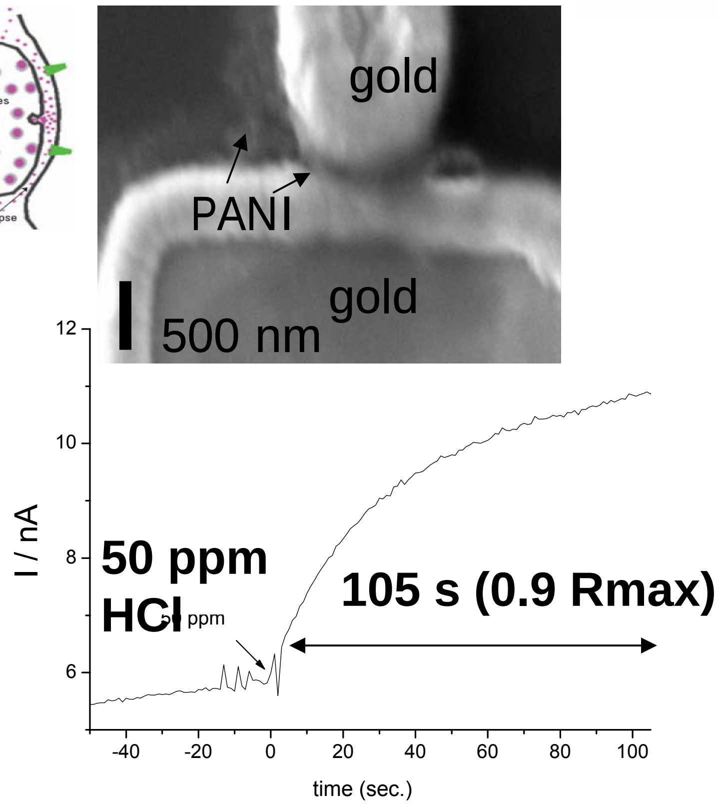
Díaz Aguilar, E. Forzani, X. Li, L.A. Nagahara, I. Amlani, R. Tsui and N.J. Tao (in preparation),2004.

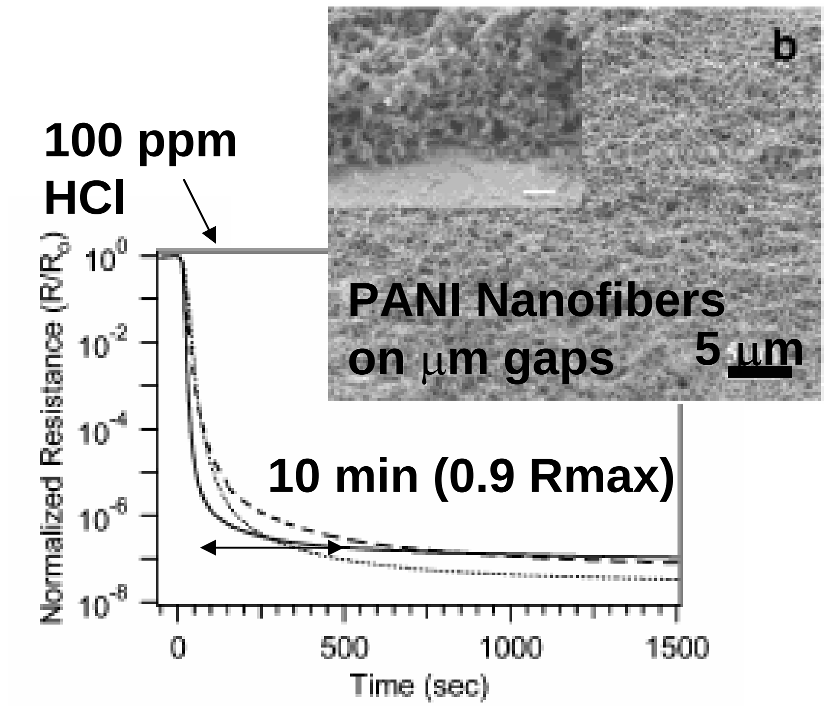
Other example of conducting polymer nanojunctions:

- Ammonia/HCl vapor detection:







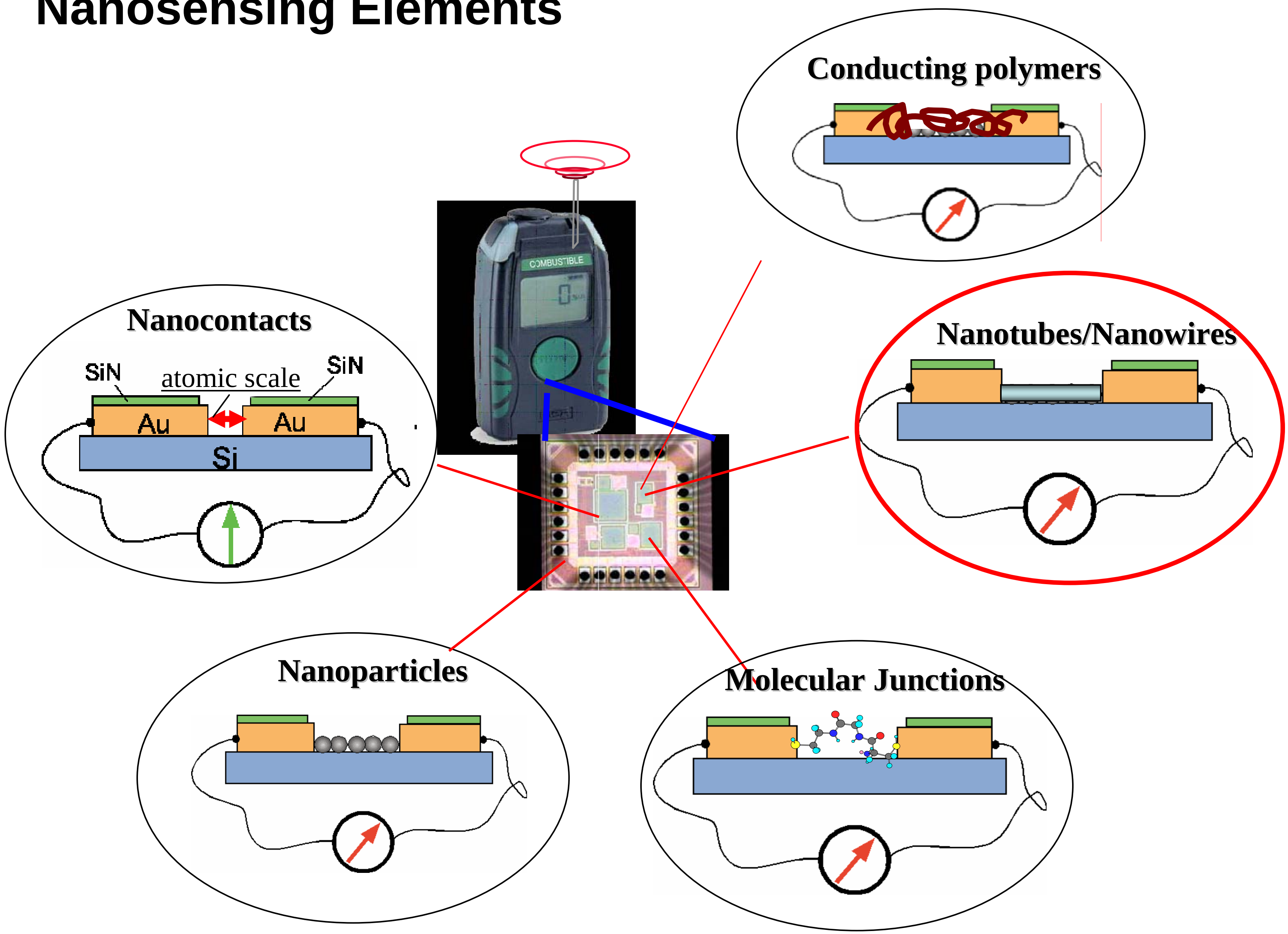


Díaz Aguilar, E. Forzani, X. Li, L.A. Nagahara, I. Amlani, R. Tsui and N.J. Tao (in preparation),2004.

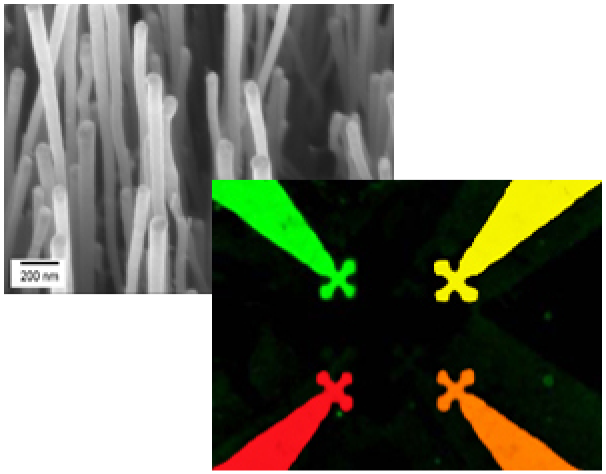
J. AM. CHEM. SOC. 2003, 125, 314-315, NANO LETTERS 2004, Vol. 4,No. 3, 491-496

No only dimensions of the sensing elements but also distribution and size gap in FET is important to get good analytical performance.

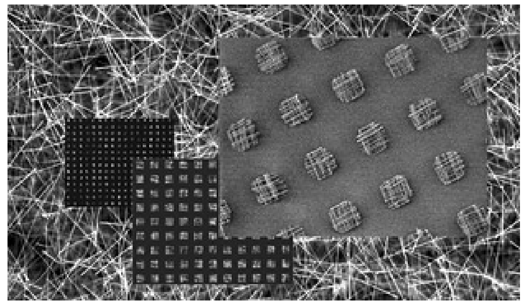
Arrays of Electrically Wired Nanosensing Elements



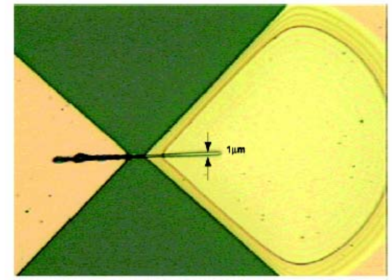
Nanotubes/wires/belts Sensors



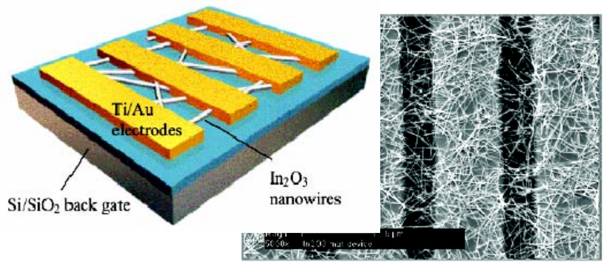
R.J. Hamers & co-workers
(http://hamers.chem.wisc.edu/)



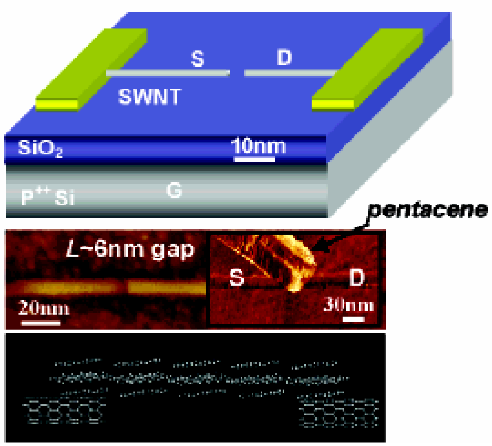
C.M. Lieber and co-workers
(http://cmliris.harvard.edu/)



N.V. Myung & co-worker + collaborators
http://www.engr.ucr.edu/~myung/Research.htm

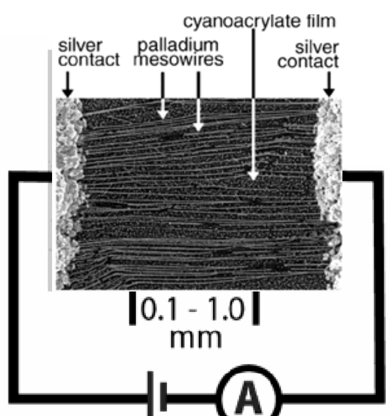


Chongwu Zhou & co-workers,
http://ee.usc.edu/faculty_staff/bios/zhou.html



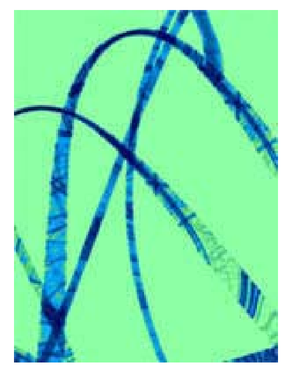
H.J. Dai and co-workers
(http://www.stanford.edu/dept/chemistry/faculty/dai/group/hongjie.html)

Nanotubes



R.M. Penner and co-workers
(http://www.chem.uci.edu/people/faculty/rmpenner/)

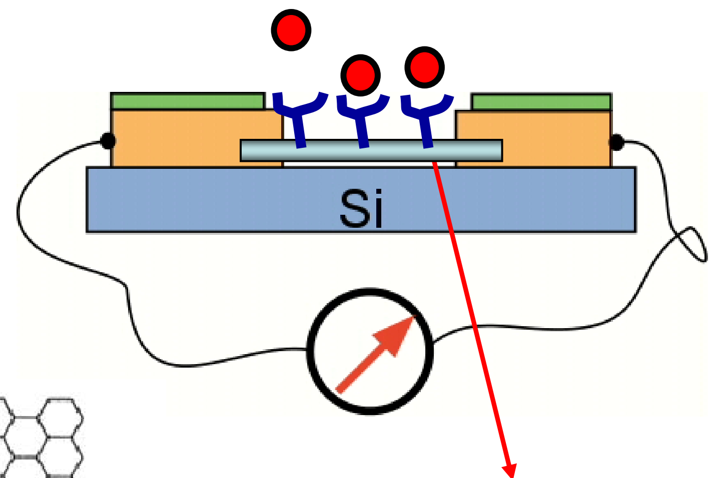
Nanowires

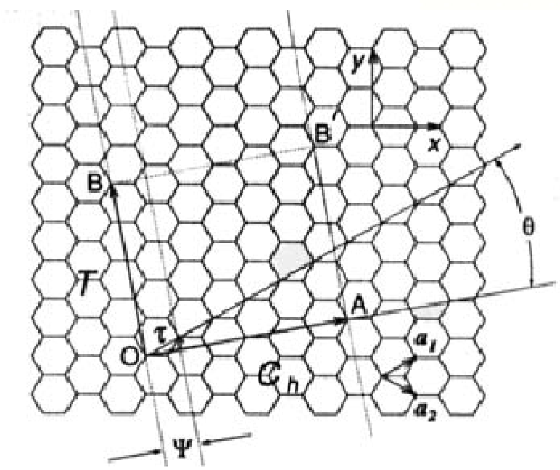


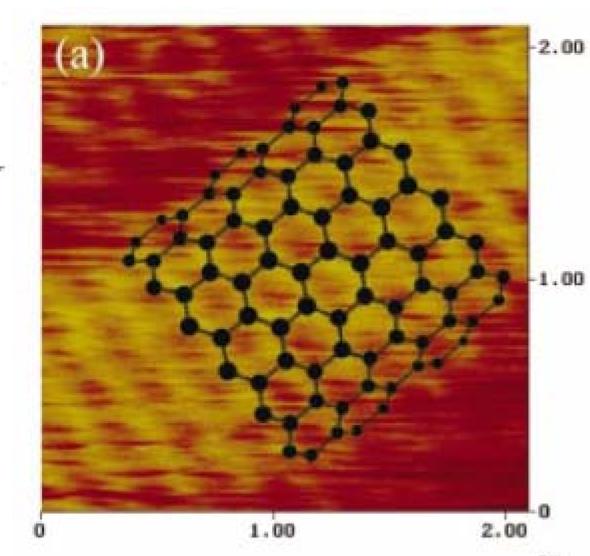
Z.L. Wang and co-workers
(http://www.nanoscience.gatech.edu/zlwang/Research.htm)

Nanobelts

Carbon Nanotube FET Sensors

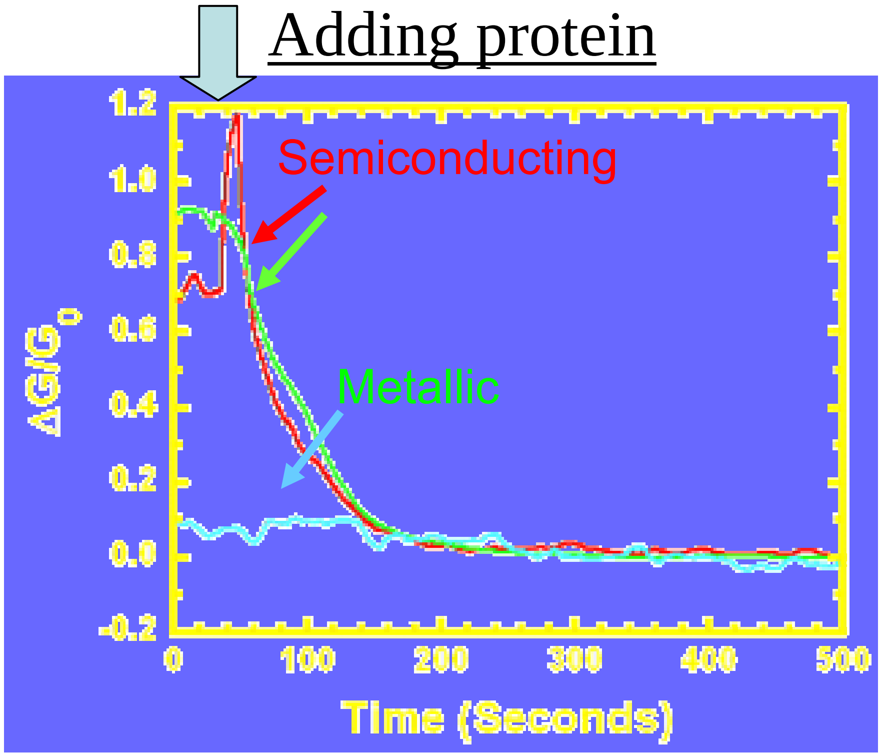


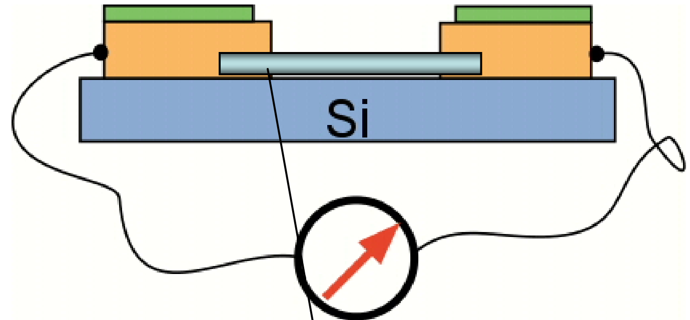


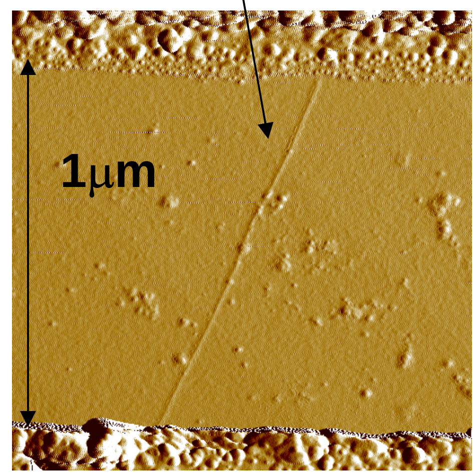


•Kong, J.; et al. *Science* **2000,** *287*, 622.
•Zhou, C.; Kong, J.; Dai, H. *Appl. Phys. Lett.* **2000,** *76*, 1597.
•Collins, P. G.; Bradley, K.; Ishigami, M.; Zettl, A. *Science* **2000,** *287*, 1801.
•Hassanien et al., Appl. Phys. Lett., Vol. 79, No. 25, 17 December 2001

Protein Adsorption on bare carbon nanotubes





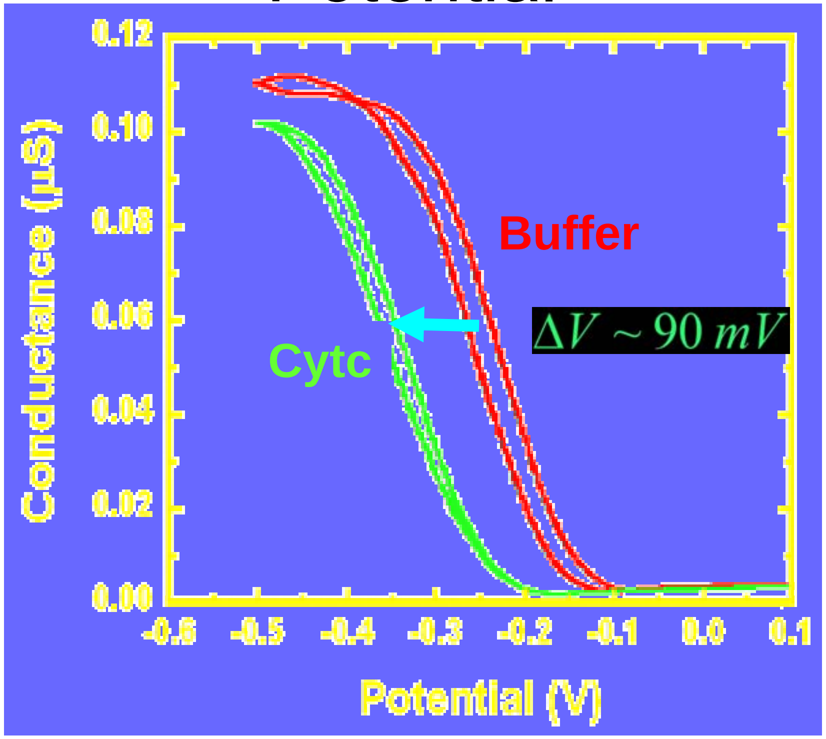


AFM image of single wall carbon nanotube (SWNT)

The protein decreases the conductance of p-type SWNT → it decreases p-type carriers number

Boussaad S, Tao NJ, Zhang R, Hopson T, Nagahara LA
CHEM. COMM. (13): 1502-1503 2003

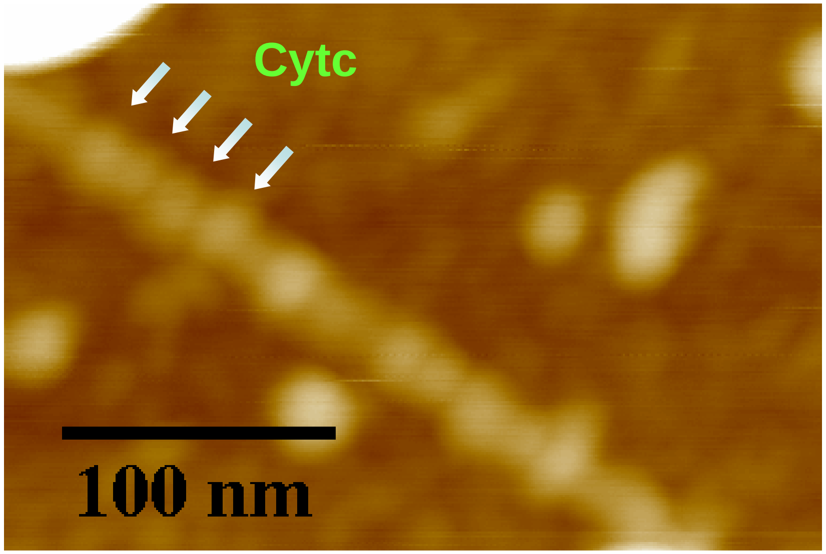
Conductance vs. Electrochemical Gate Potential



Partial charge transference

$$\#\,\mathrm{Cytc} = \frac{4x10^{-10}\,\mathrm{F/m} \times 10^{-6}\,\mathrm{m} \times 0.09\,\mathrm{V}}{10\,x\,1.6x10^{-19}\,\mathrm{C}}$$

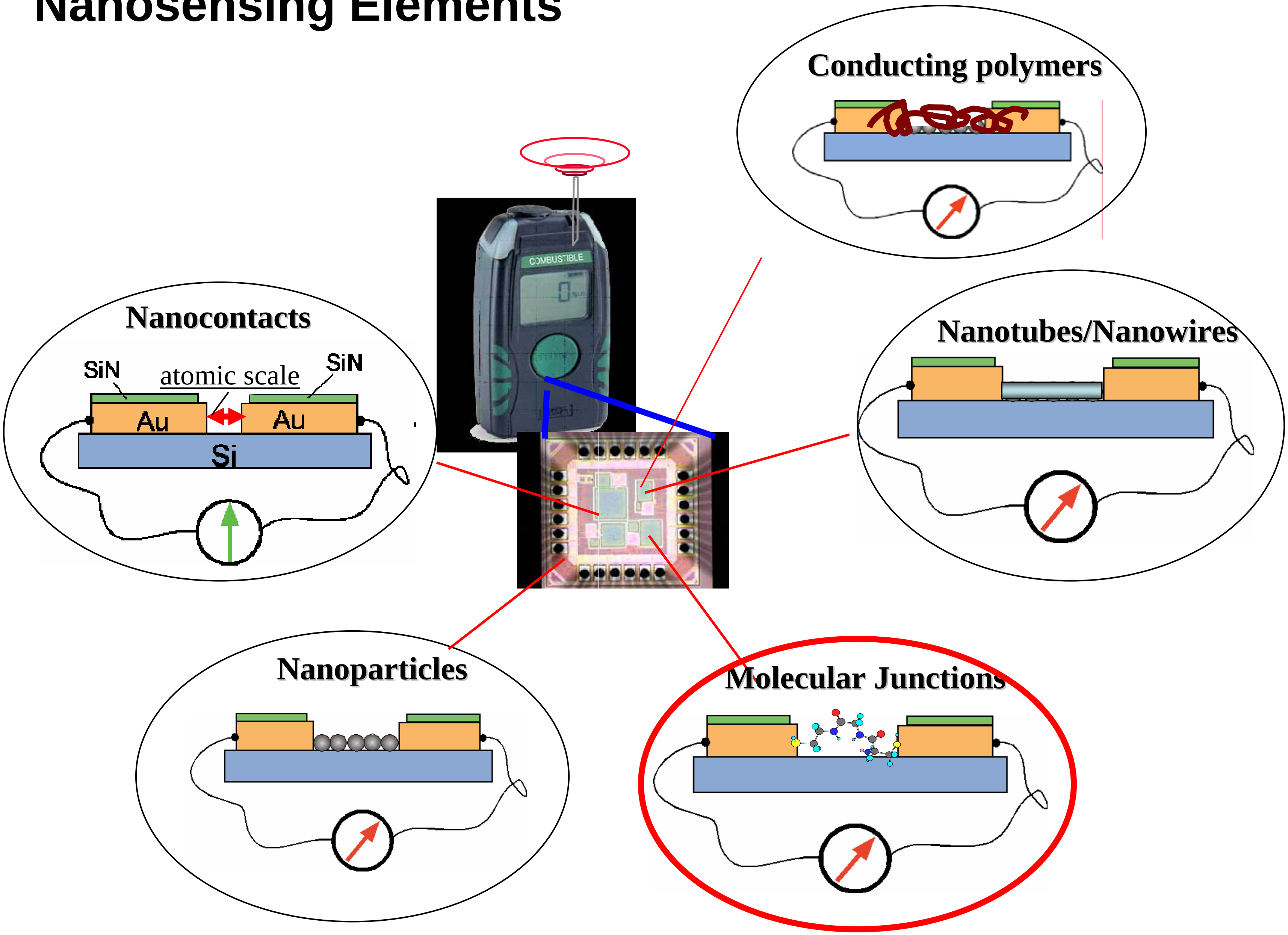
$$= \sim 20\ \mathrm{Cytc\ molecules}$$



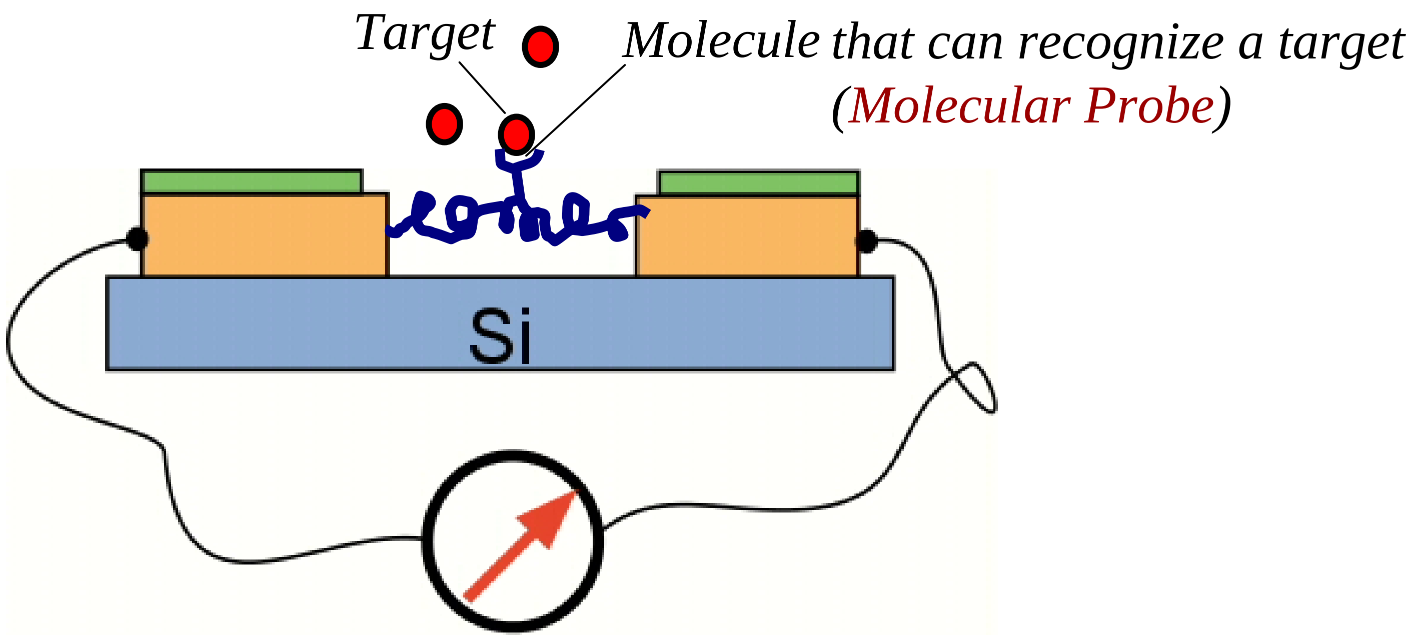
Based on the AFM images, the number of Cyt C molecule adsorbed onto the SWNT is ~30-40.

Boussaad S, Tao NJ, Zhang R, Hopson T, Nagahara LA
CHEM. COMM. (13): 1502-1503 2003

Arrays of Electrically Wired Nanosensing Elements

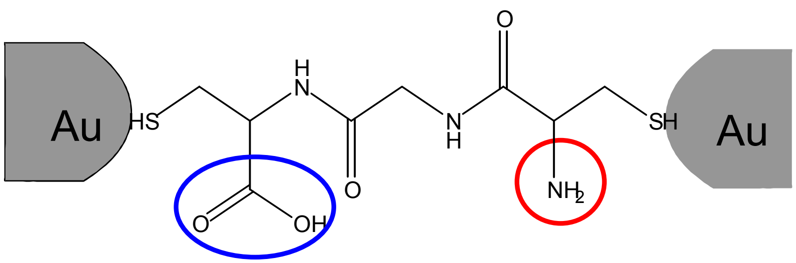


Molecular Junction Sensor

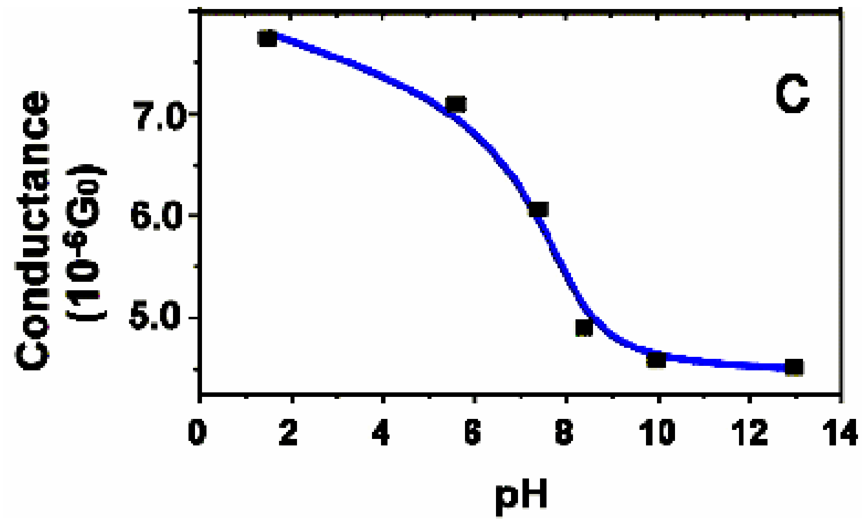


✓ Direct approach
✓ Single molecule detection

pH Sensor

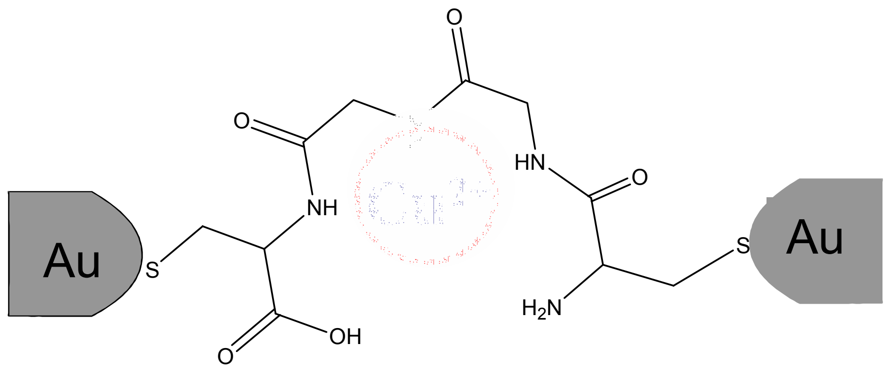


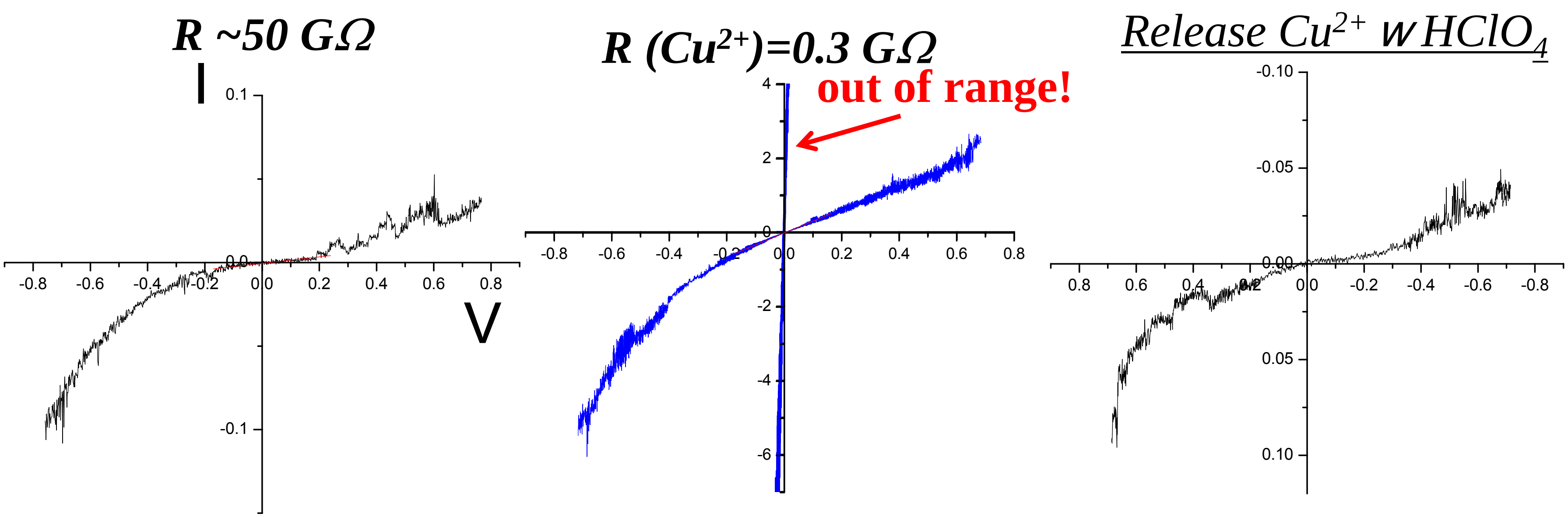
Cys-Gly-Cys



Xiao XY, Xu BQ, Tao NJ, JACS 126 (17): 5370-5371 MAY 5 2004

Metal Ion Detection



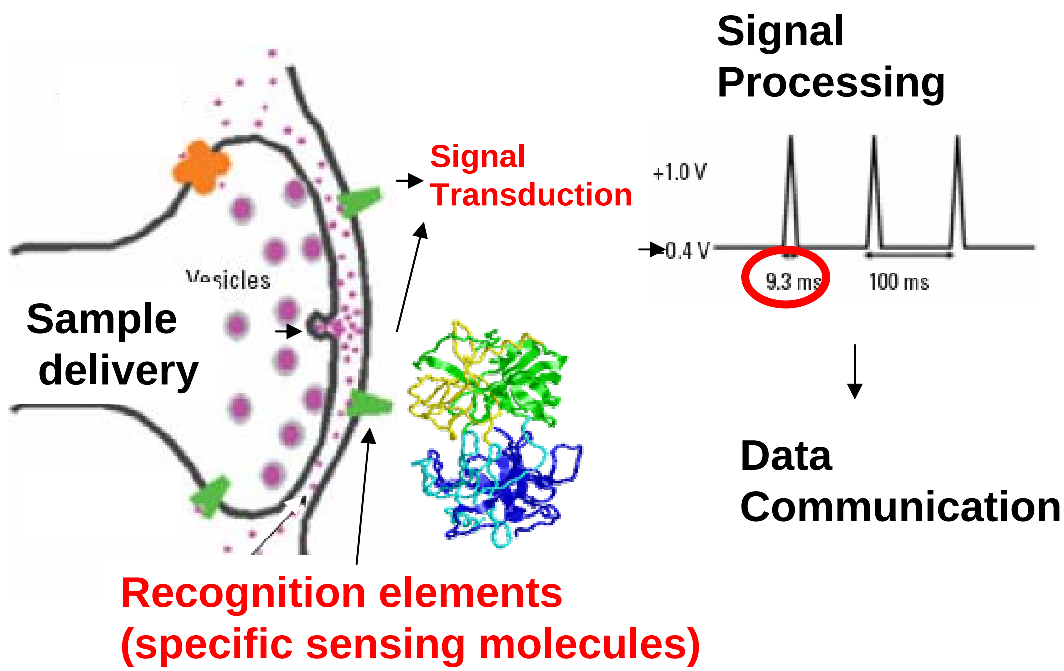


- ✓ Conductance increases upon Cu^{2+} binding
- ✓ Metal ion dependence (Cu^{2+} vs. Ni^{+} ions)

300 higher for Cu^{2+}, 100 higher for Ni^{2+}

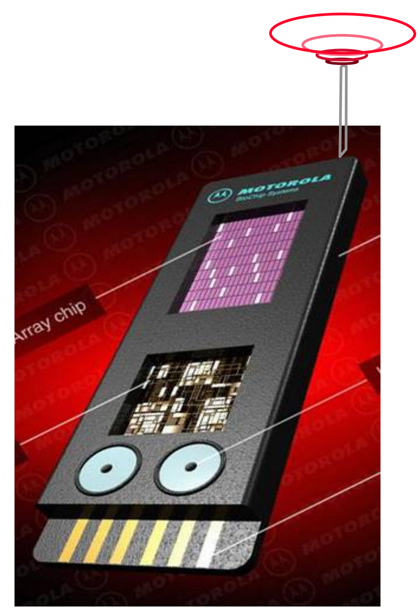
Xiao XY, Xu BQ, Tao NJ, Angew. Chem. (asap) 2004

What is the progress achieved to date trying to emulate nature ?



An Integrated Nanosensor
for Simultaneous Detection of A Range of Species

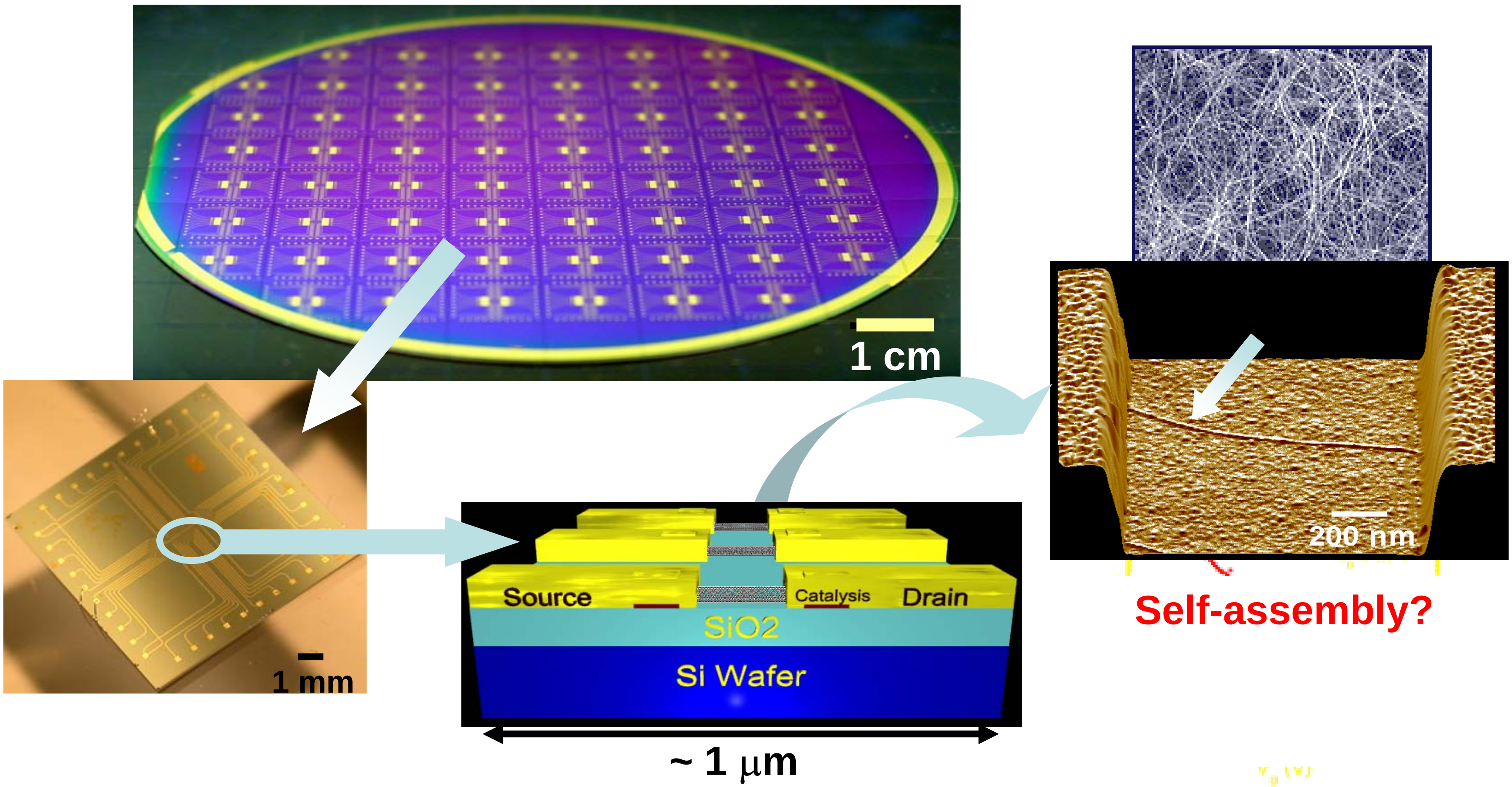
- ✓ Highly sensitive and selective individual nanosensors demonstrated.
- ✓ Common platforms for simultaneous detection of different species demonstrated.



What are the challenges ahead ?

Microtechnology Meets Nanotechnology

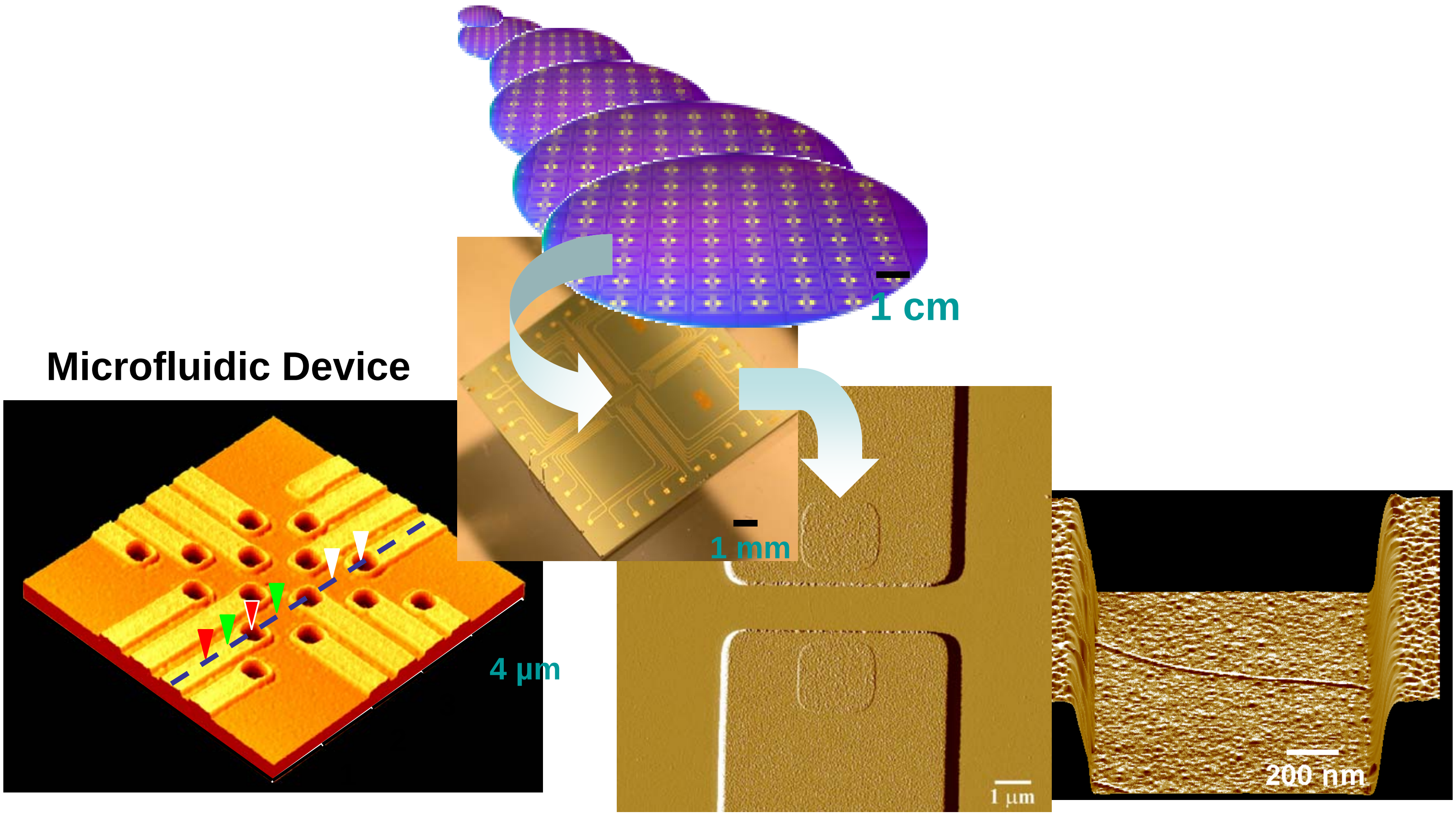
- Interconnection Issues



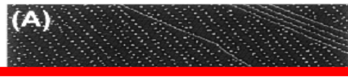
Challenges Ahead

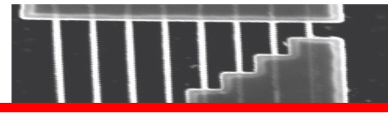
Microtechnology Meets Nanotechnology

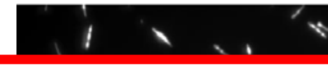
- Sample Delivery



Nano-Solution to Big Sensor Problems?







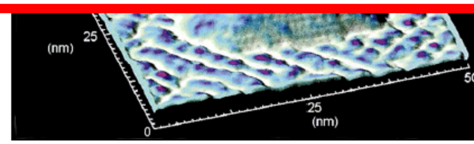
Unique Features:

✓ Reduced sample solutions
✓ Small size promises high degree of integration
✓ High sensitivity for single molecule/ion analysis
✓ Fast response time

Remaining Challenges:

*An **integrated** device needs to solve the interface between Nano- and Micro-technology:*

✓ Interconnection issues
✓ Sample delivery



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