“Semiconductor Nanowires for Electronics, Photonics & Sensorics”

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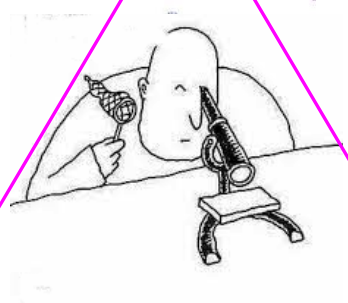
Outline:

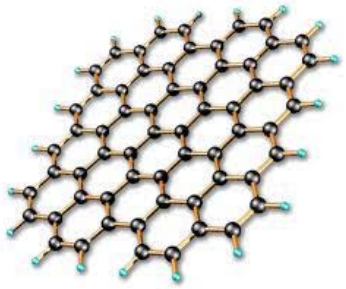
- Nanotechnology: key elements; market forecast
- Nanomaterials
  - nanowires: what, why, how?
- Nanodevices:
  - Applications for energy, sensorics, optoelectronics

Nanotechnology: Materials, Tools and Devices

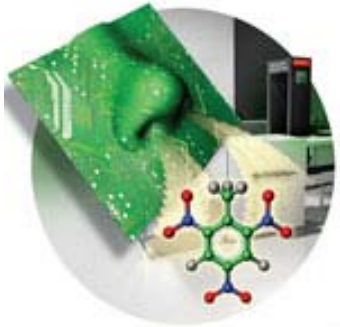


Tools & Metrology

Materials



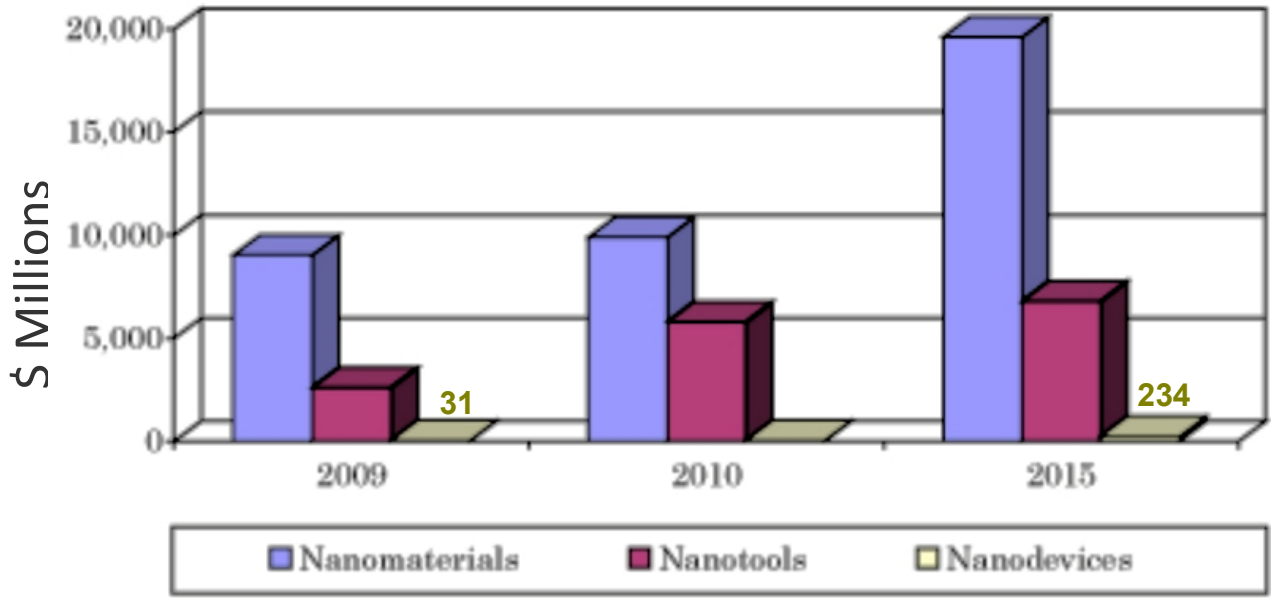
Devices



- Instrumentation made nano-materials and nano-devices achievable!

Nanotechnology: Market Assessment

Global Nanotechnology market, 2009-2015

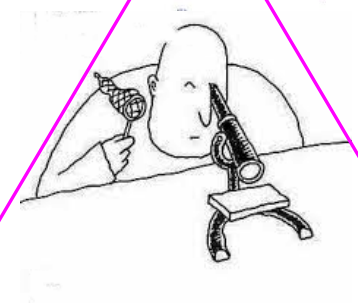


Source: BCC Research

[Nanotechnology: A Realistic Market Assessment
Report Code: NAN031D, Published: July 2010]

- "Growth of $26 Billion in 2015 is more honest than $2.95 Trillion forecast" [Nanowerk]
- "Nanodevice category will experience moderate growth" [BCC Research]

"… в течение 20 лет в кровь будут внедрены тысячи нанороботов, которые будут следить за здоровьем, улучшать производительность и создавать резервные копии содержимого мозга, как файлы на компьютере" [Raymond Kurzweil , Future Talk, Oct 20, 2010]

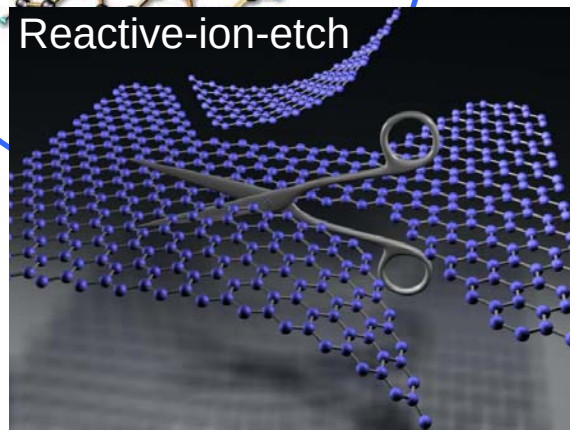


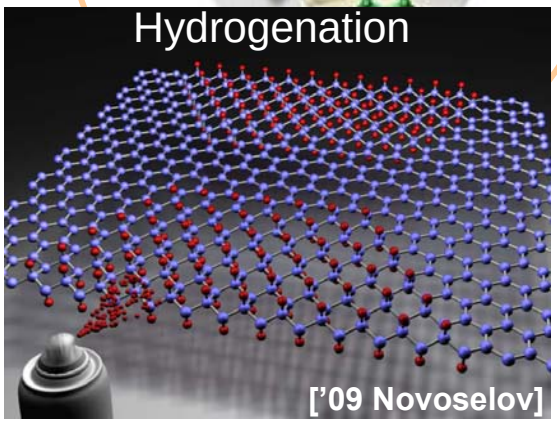
Metrology & Tools

Materials

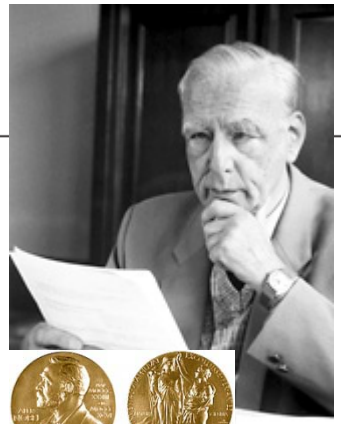
Devices

- Key advancements:
  - fabrication on nanometer/atomic scale
  - Imaging of properties/structure with nm/atomic resolution



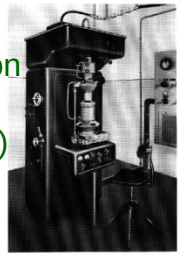


Tools: 77 Years of Electron Microscopy => *Nanoscopy!*

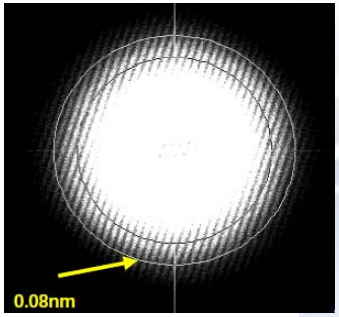


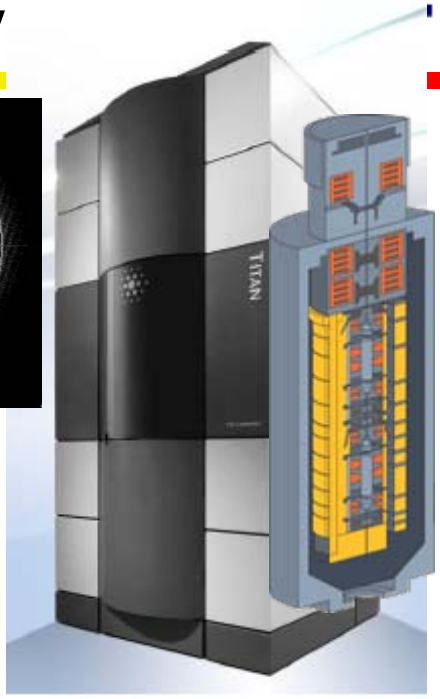
1986

Electron microscope

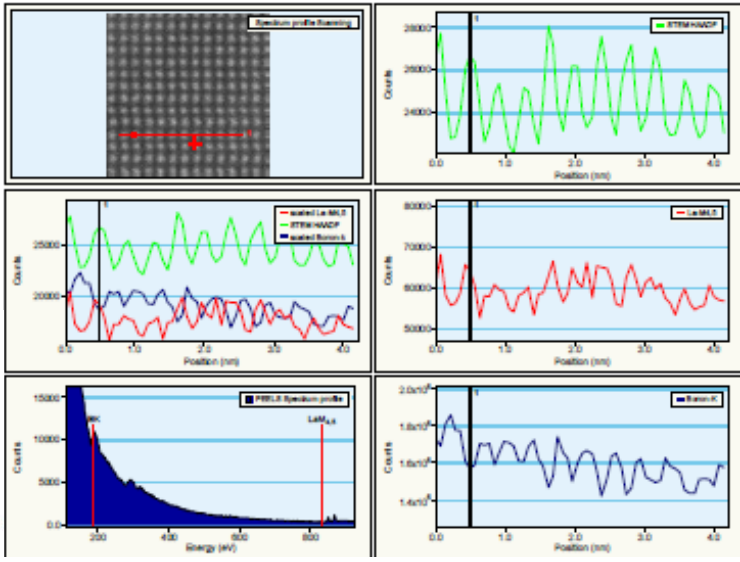


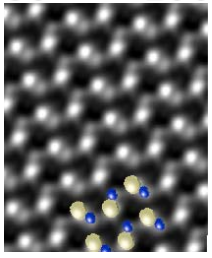
The first electron microscope (Siemens 1940)

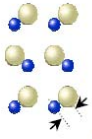




FEI Titan AC TEM/STEM for nanoscopy with the atomic resolution and sensitivity



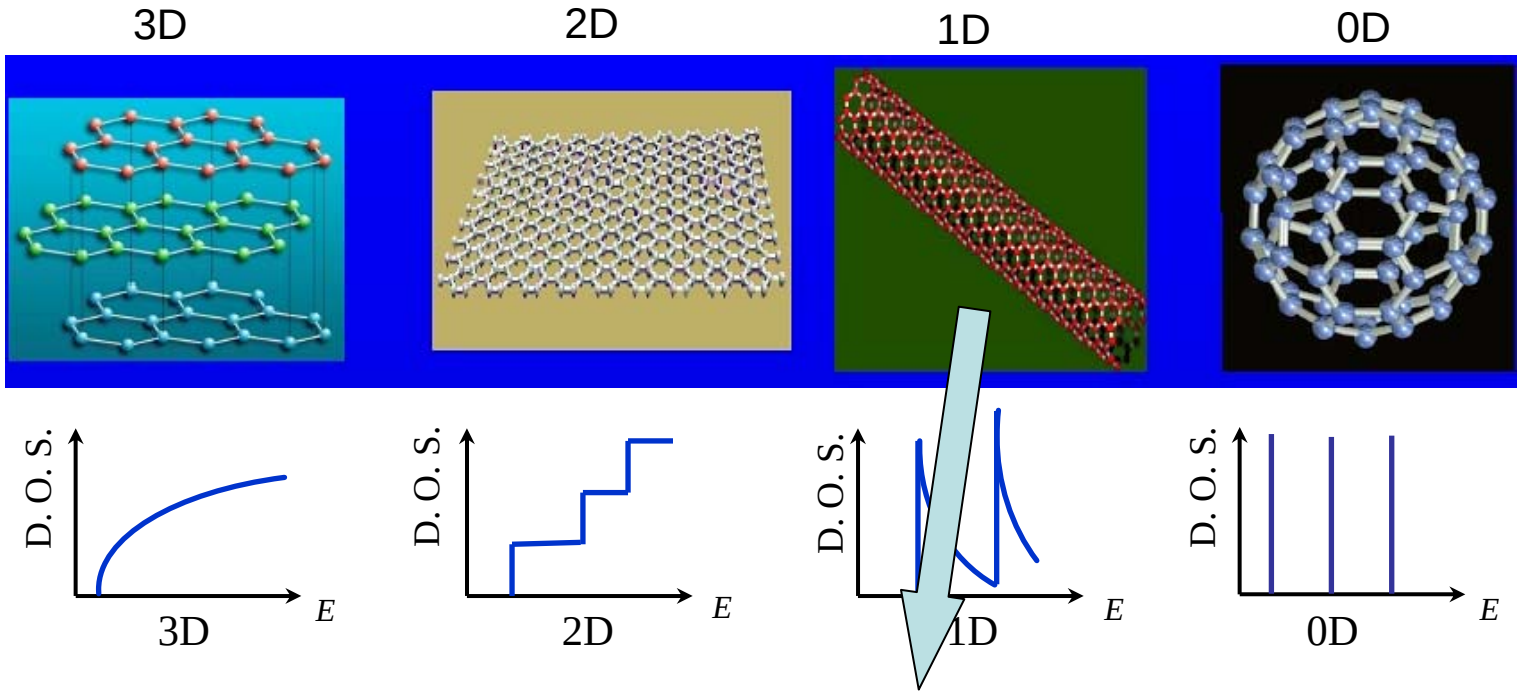




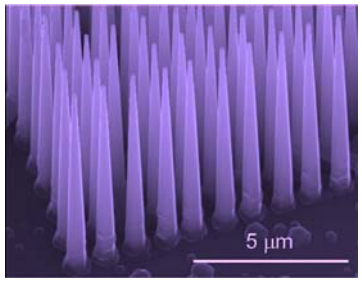
Atomic level EELS microanalysis

[Courtesy of Vladimir Oleshko, NIST]

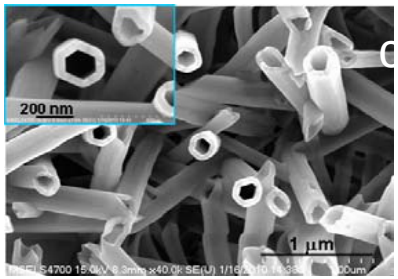
Nanomaterials: building blocks



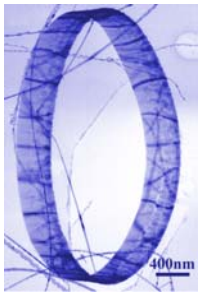
Si nanowire array (NIST)



GaN nanotubes (NIST)

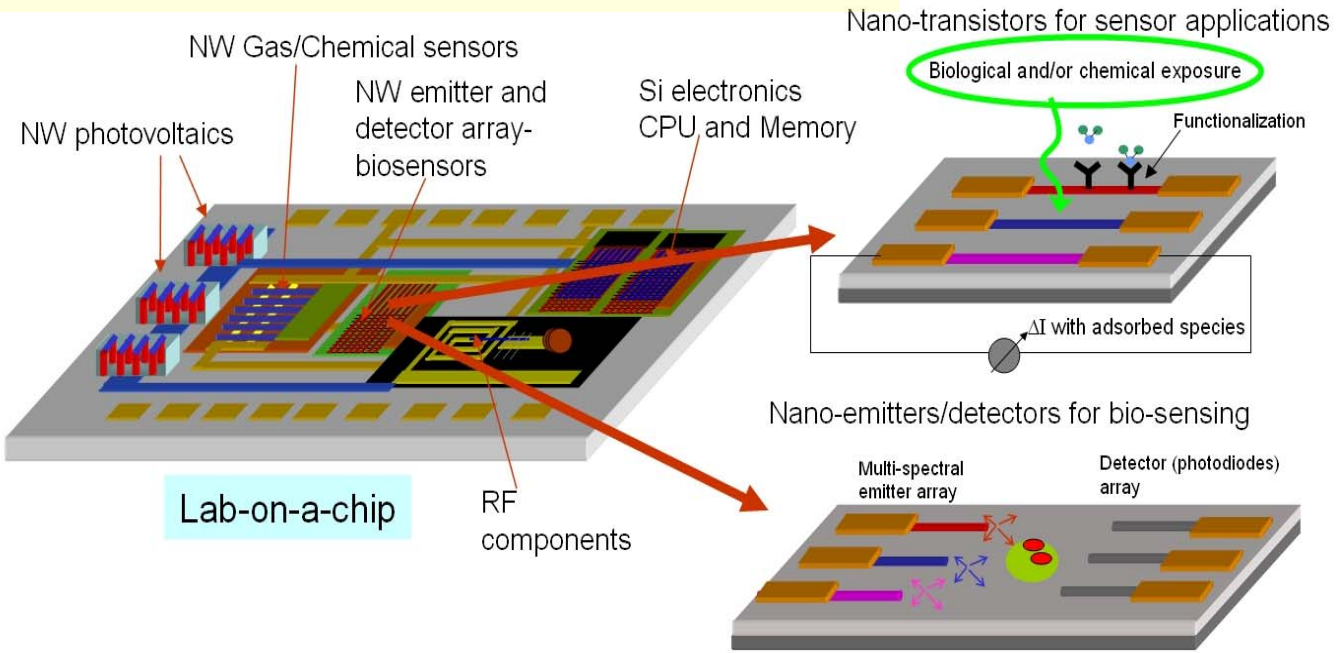


ZnO nanoribbons [ZL Wang]

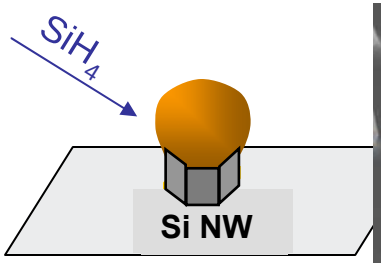


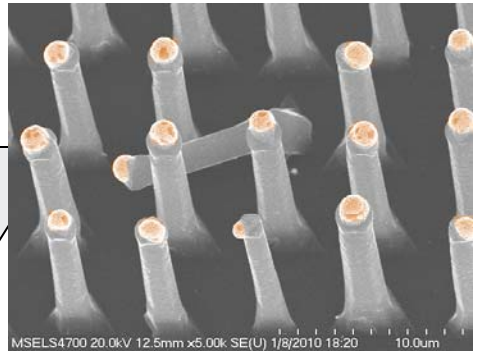
Why Nanowires?

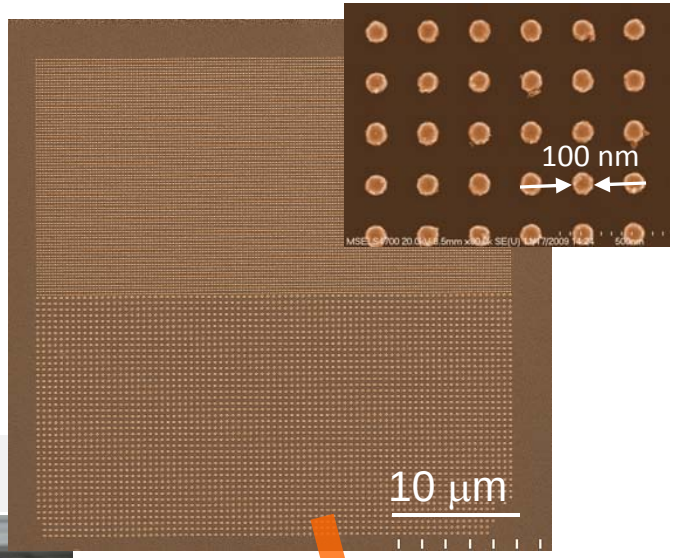
- Building blocks for bottom-up assembly (lab-on-chip)
- Applications:
  - Opto: LEDs and lasers; optical modulators/waveguides; photodetectors
  - Energy: solar cells, piezo-generators, batteries, thermoelectrics
  - Sensors: gas/chemi-/bio- multiplex sensing
- Properties (new/enhanced functionality):
  - defect-free single crystals
  - high surface-to-volume ratio
  - controllable shape, electronic properties
  - size-confinement effects



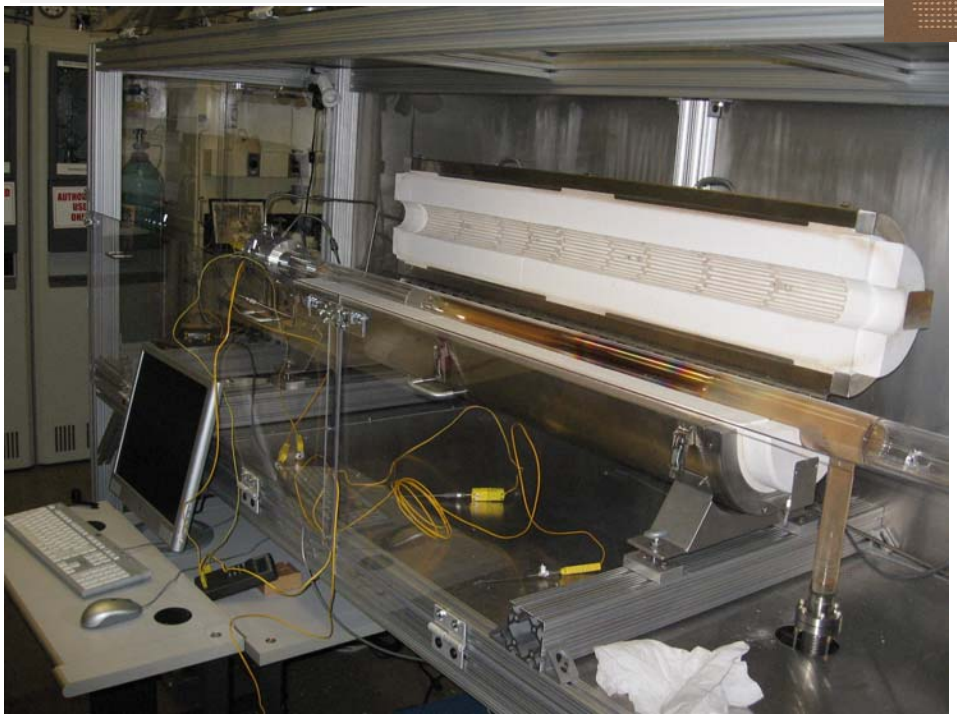
How Do Nanowires Grow?



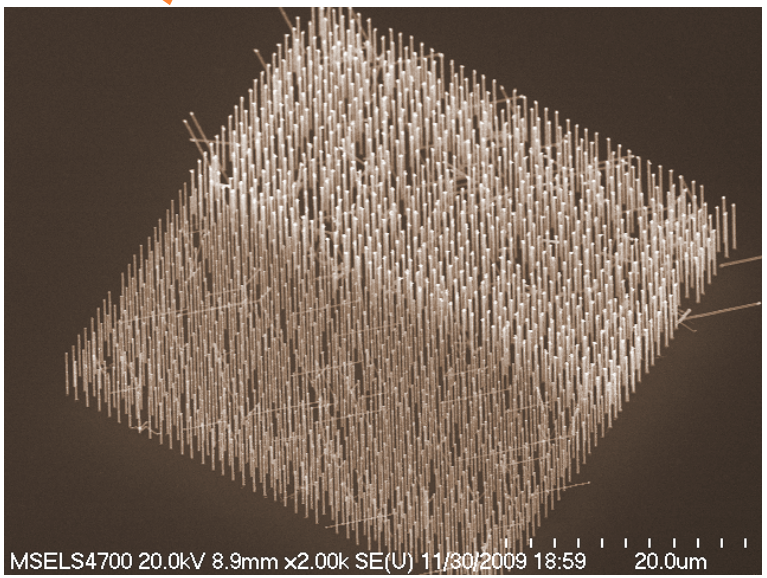




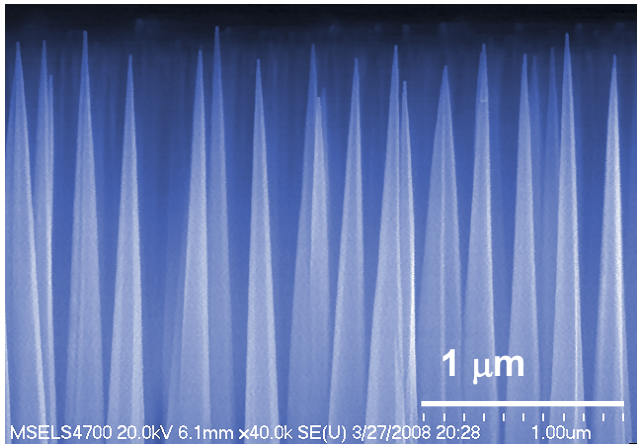
Catalyst-assisted Growth of Si Nanowires



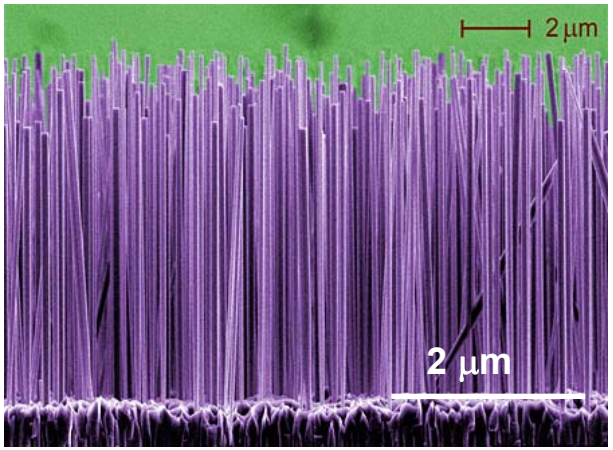
Horizontal hot-wall reactor for Si NW growth



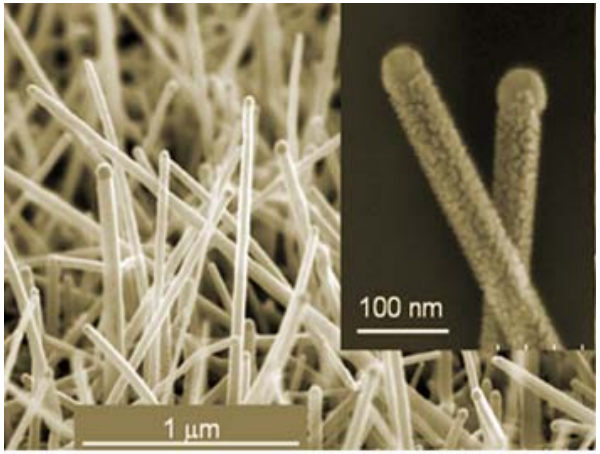
Semiconductor NW Growth at NIST



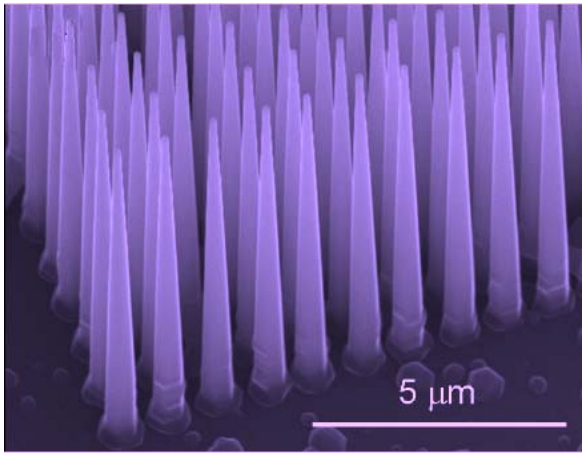
AlN by HVPE (D. Tsvetkov)



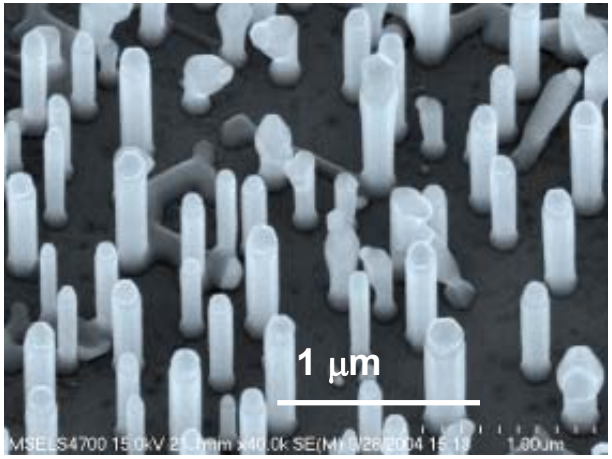
GaN by MBE (K. Bertness)



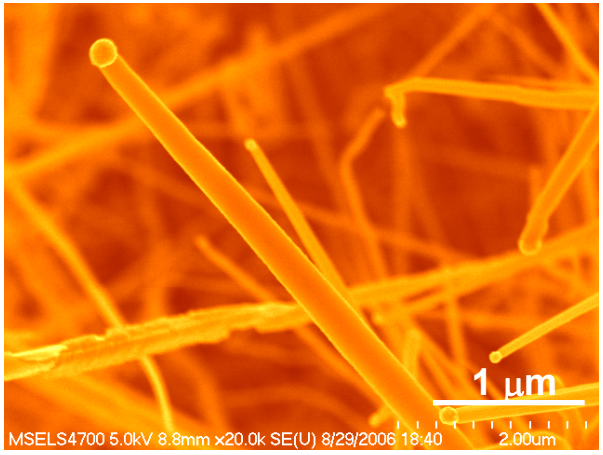
GaN by HVPE (D. Tsvetkov)



Si by CVD (S. Krylyuk)

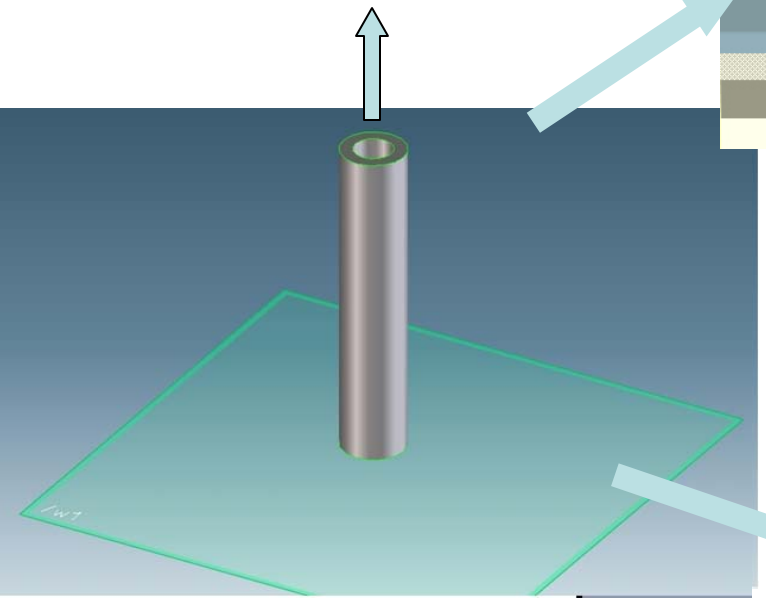


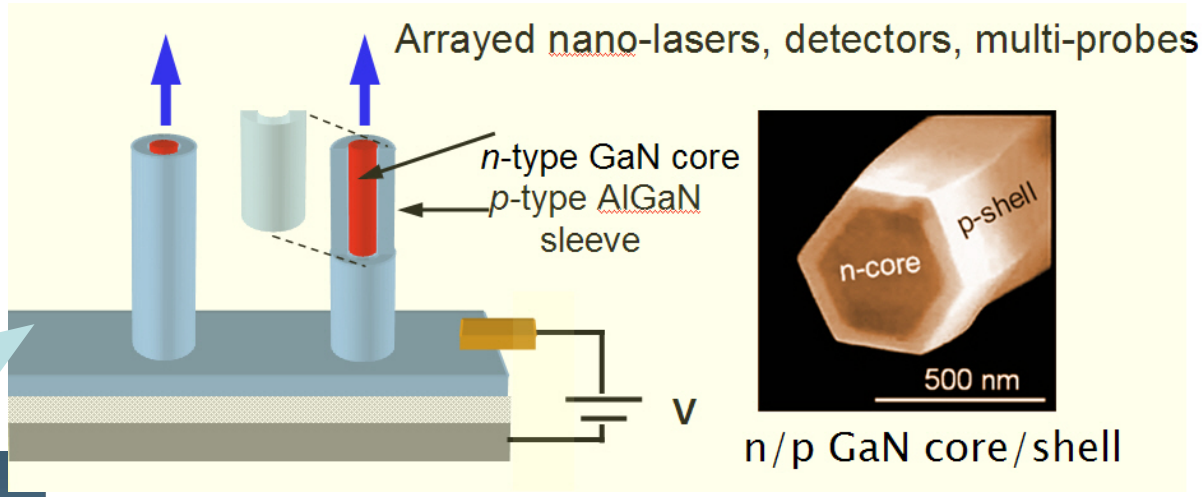
ZnO by CVD (B. Nikoobakht)



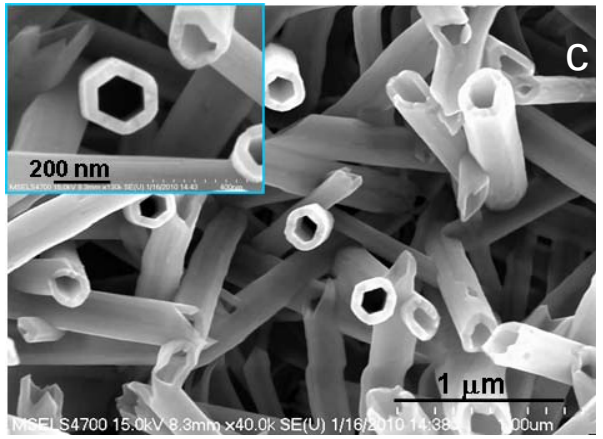
SiC by sublimation (S. Sundaresan)

GaN Core-Shell Nanowires & Nanotubes



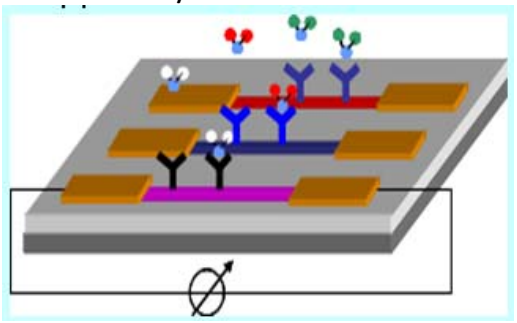


Drug delivery tools

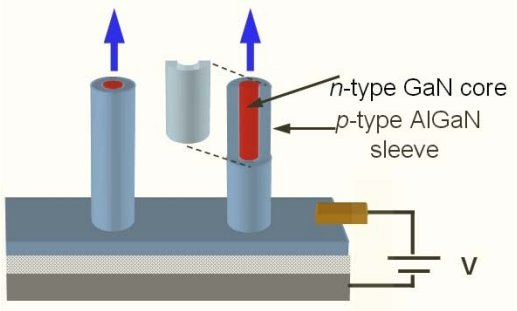


GaN nanotubes

Bio-/chemi- sensors

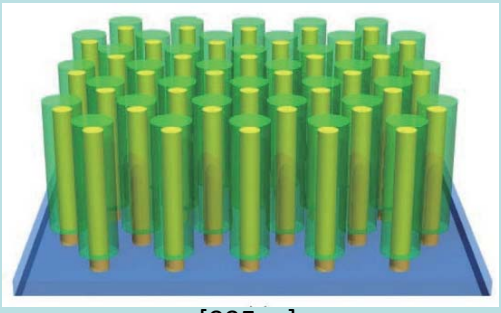


LEDs, lasers, detectors



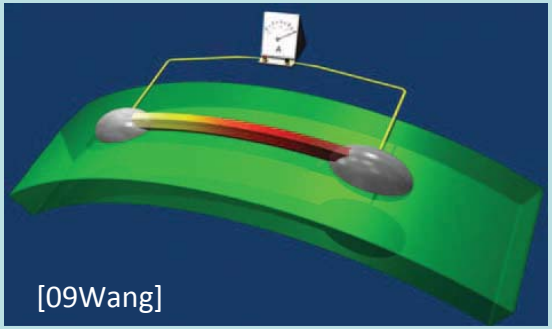
ENERGY

Photovoltaics

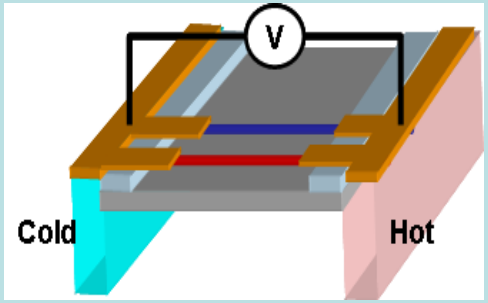


[09Fan]

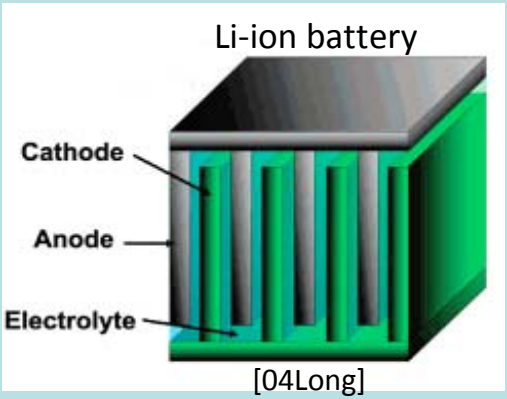
Piezoelectric generators



Thermoelectrics



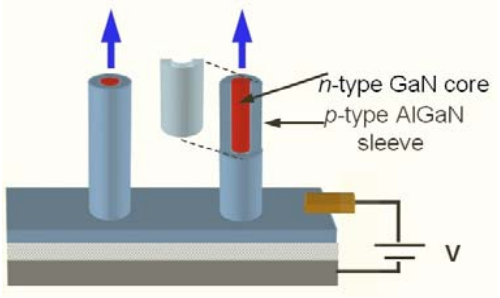
Li-ion battery

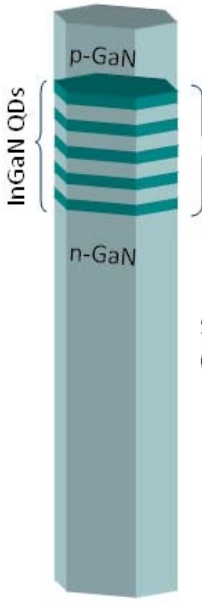


[04Long]

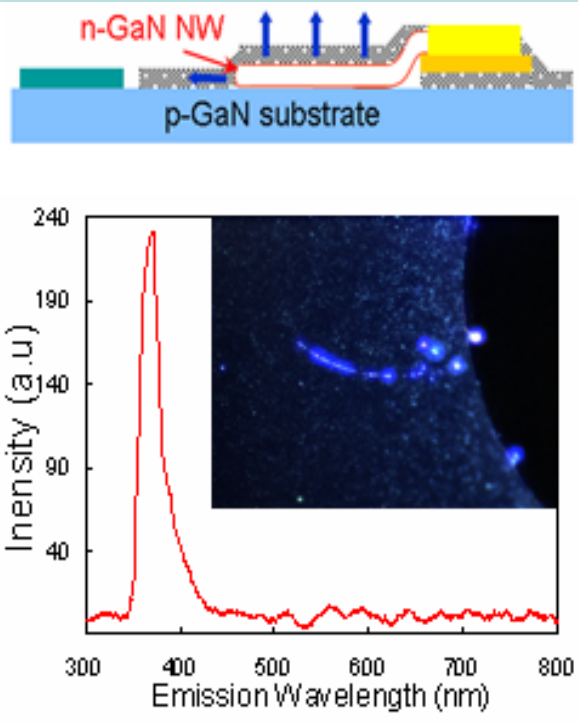
GaN nano-LED

LEDs, lasers, detectors

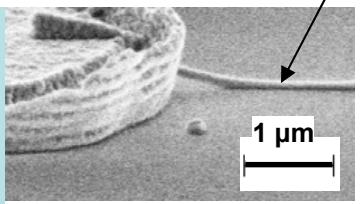




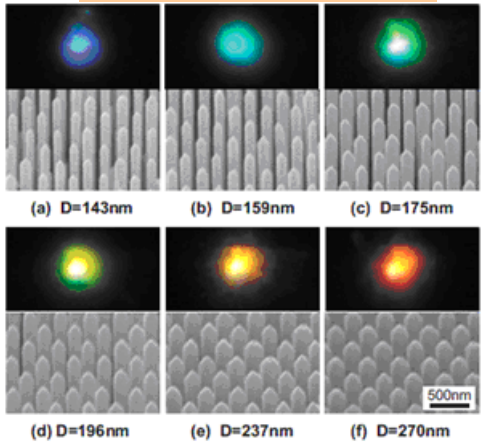
Structure of
Single NW LED



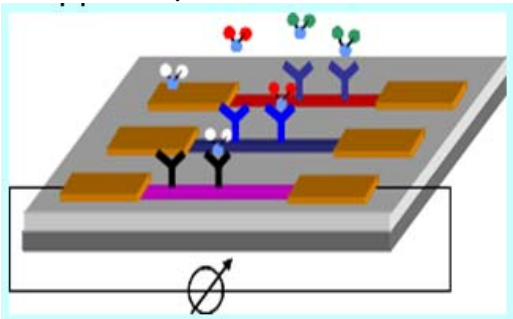
GaN NW LED [NIST]



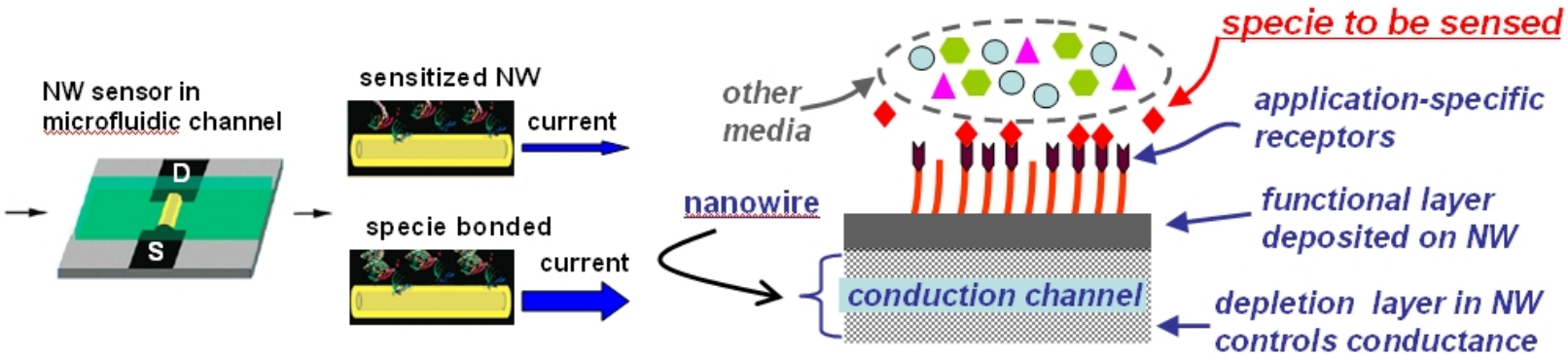
All-color LED [10Kishino]



Bio-/chemi- sensors

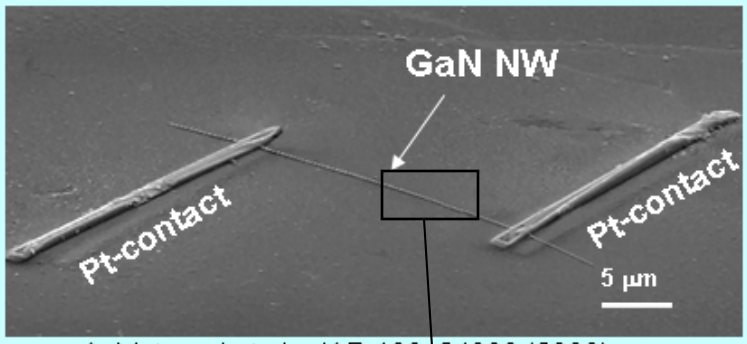


Functionalized FET Nanowire-Biosensor Heterostructures

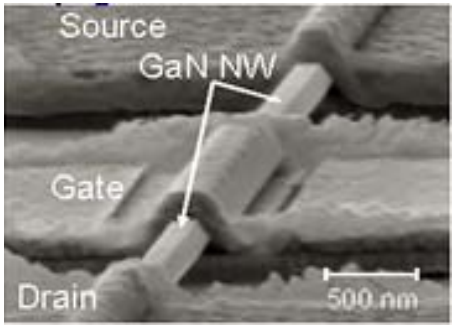


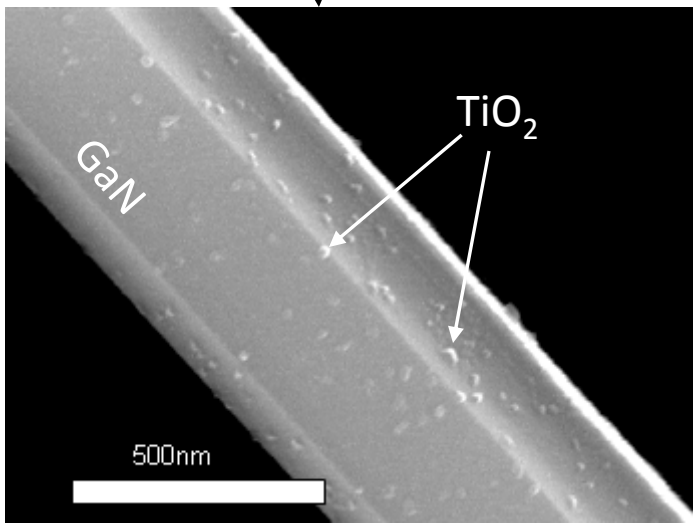
Channel conductance changes when target specie bonds to receptor

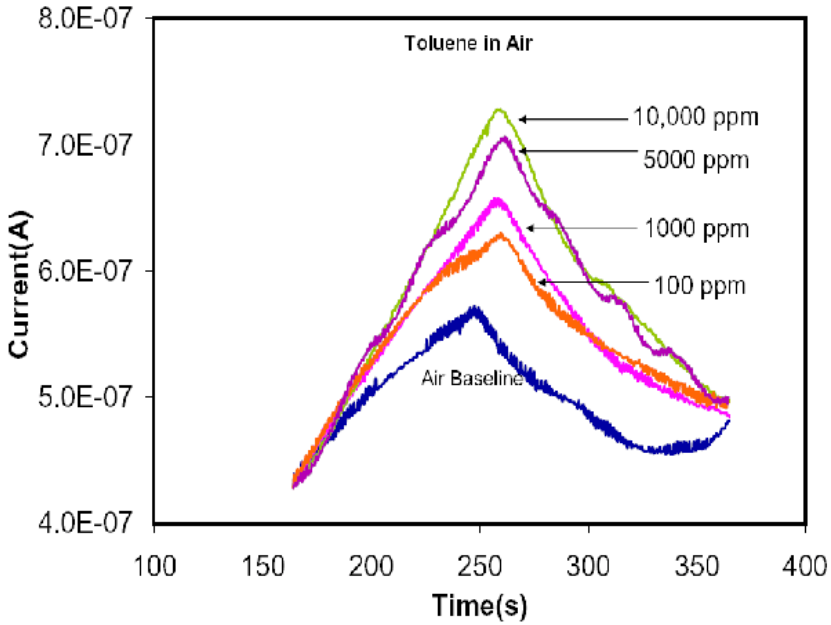
GaN Gas Sensors (Chemiresistors)



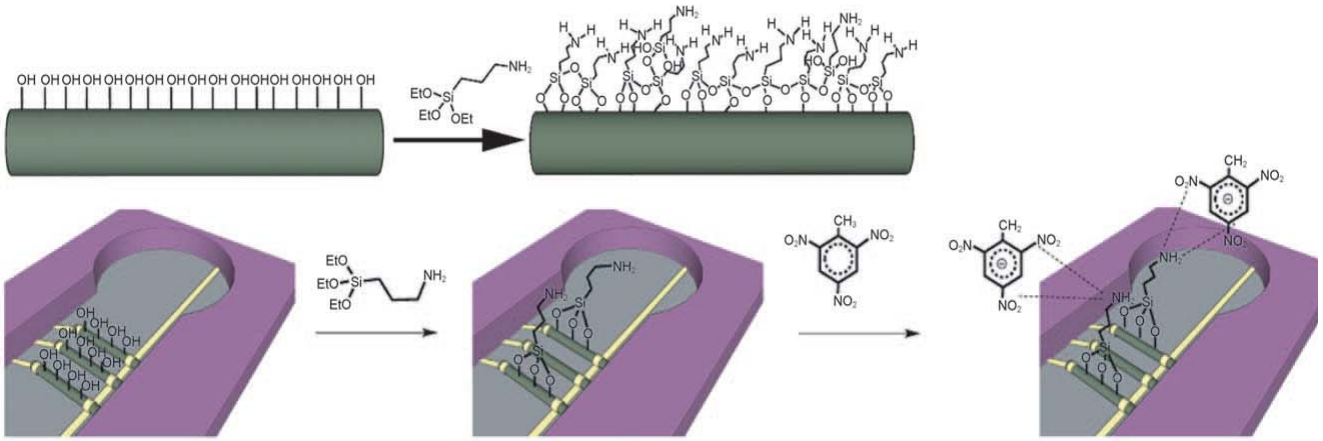
A. Motayed et al., JAP 100, 24306 (2006)

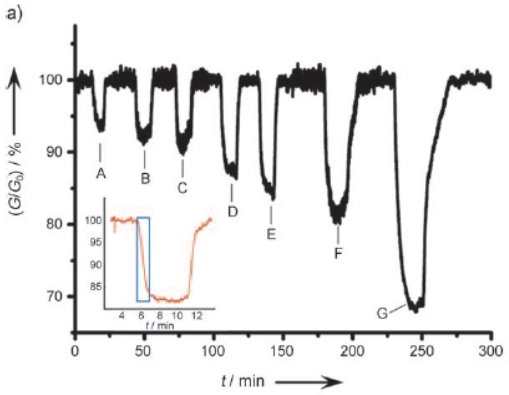






Si NW Sensor for TNT [10Engel]

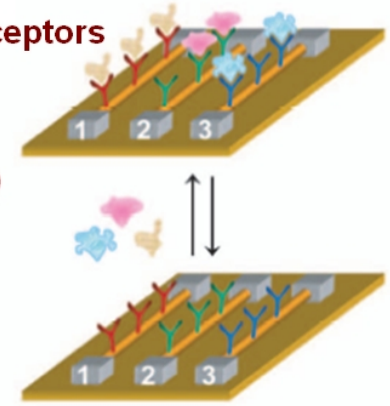


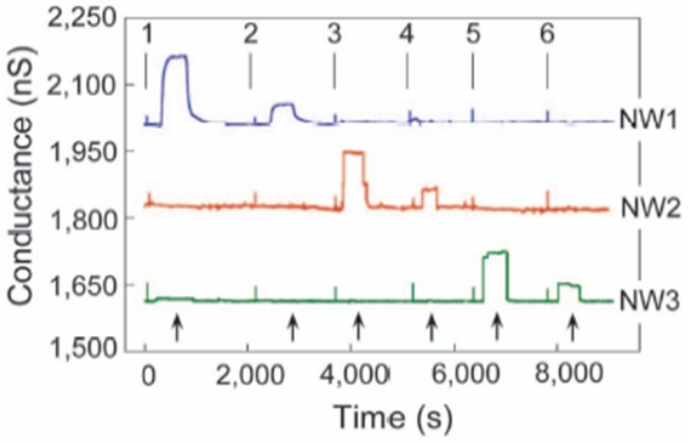


Integrated NW FET sensors specific to 3 different cancer markers [Lieber]

Functionalized with monoclonal receptors specified for:

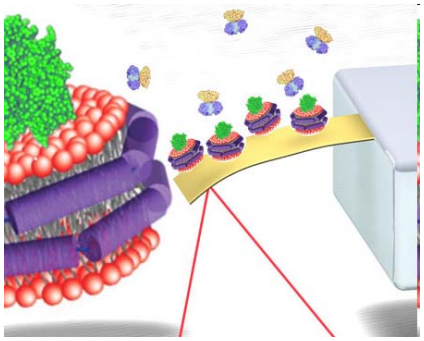
1. **Prostate specific antigen (PSA)**
2. **Carcinoembryonic antigen (CEA)**
3. **Mucin-1**

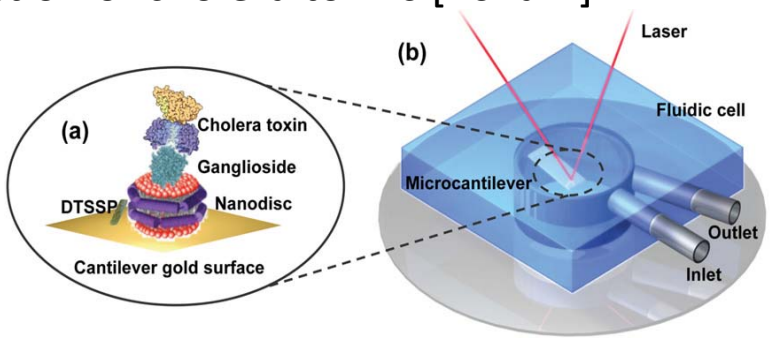


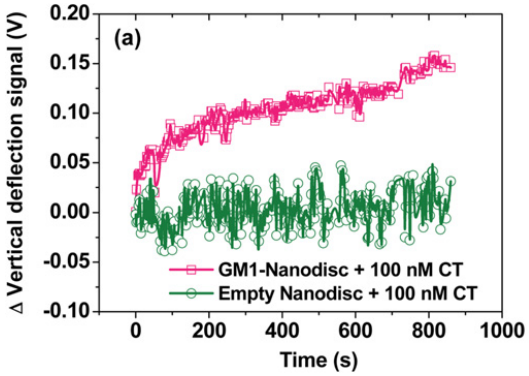


More Sensors

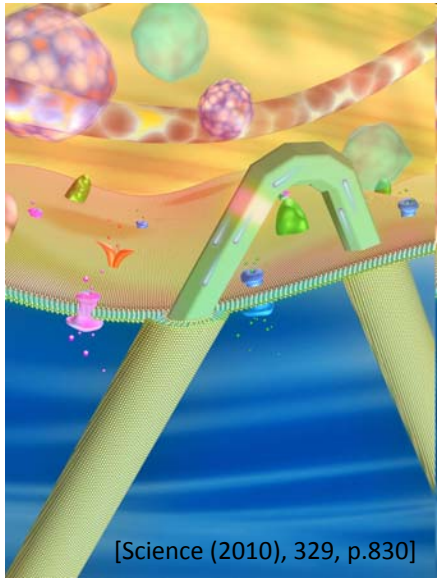
Nanomechanical detection of cholera toxins [10Tark]

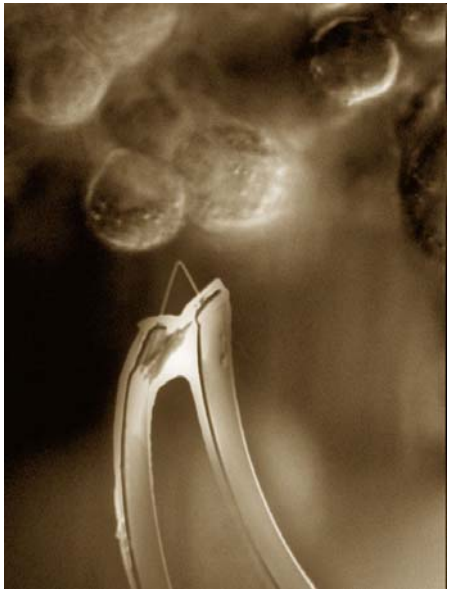






Electronic sensor probe inside a cell [Lieber]





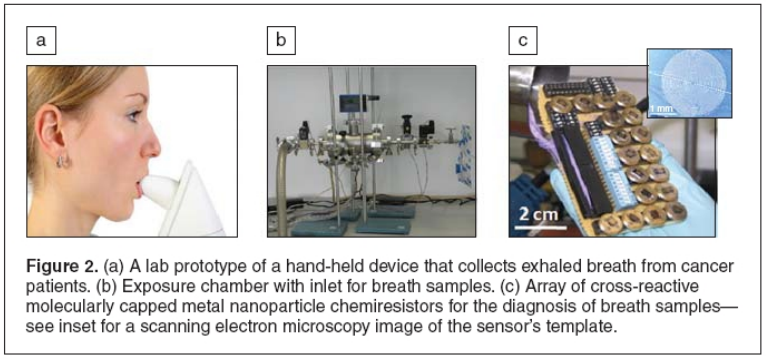


Figure 2. (a) A lab prototype of a hand-held device that collects exhaled breath from cancer patients. (b) Exposure chamber with inlet for breath samples. (c) Array of cross-reactive molecularly capped metal nanoparticle chemiresistors for the diagnosis of breath samples—see inset for a scanning electron microscopy image of the sensor's template.

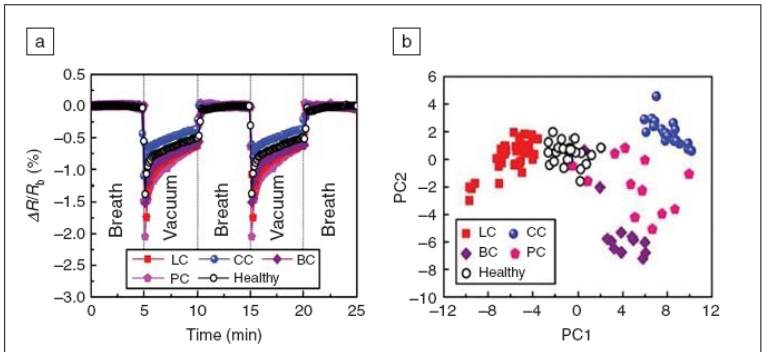


Figure 3. (a) Typical responses, $\Delta R/R_b$, of one sensor functionalized with 2-ethylhexanethiol upon exposure to breath of patients with lung cancer (LC), colon cancer (CC), breast cancer (BC), and prostate cancer (PC), as well as healthy controls, as representative examples. R_b is the baseline resistance of the sensor in the absence of analyte, and ΔR is the baseline-corrected steady-state resistance change upon exposure of the sensor to analyte. (b) An example for principle component analysis pattern recognition for LC, BC, CC, PC and healthy controls. PC1, principal component 1; PC2, principal component 2.

Summary

- Nanotechnology:
  - Instrumentation made it possible
  - Market forecast ($26B in 2015): nanomaterials > nanotools > nanodevices
- Nanomaterials:
  - Semiconductor nanowires
  - Applications: optoelectronics, electronics, energy, sensorics