EECS 598:002 Introduction to Nanoelectronics

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T,Th, 10:30-12:30
Fall, 2005

Objectives of the course

- To get students familiar with up-to-date research progress in the field of nano-science and technology, particularly in nanoelectronics

- To help students develop tools important in performing research, such as collaboration, critical thinking and presentation of your findings.

Course homepage:
http://www.eecs.umich.edu/courses/eecs598/

Structure and grading

- Lectures given on Thursdays

- Students presentations given on the following Tuesday.
  - 6 groups
  - Each group randomly chosen in class.
  - The reading materials will appear on the course homepage 2-3 weeks earlier.
  - I will emphasize the important points during the presentation and summarize the topic afterwards.

You need to address the following points:

- Background introduction
- What is new about this work (technique, methods, etc, why hasn't this been done before)?
- What are the achievements and impacts?
- Is there an alternate method (explanation)?
- What are the next logical steps?

Structure and grading

- 2-3 homework sets
- Term paper in the form of research proposal at the end of semester

Quizzes (not counted in final grading) in class – bring your calculators.

Presentation 40%

Term paper 30%

Homework 20%

Active Involvement 10%

Schedule

1. Introduction (1 week)
   - nanoscale science and technology, definition and impact
   - what's new in nano?
   - examples
2. Background on solid state devices (1 week)
   - crystal and band structures
   - envelope function
   - field-effect transistors, charge control model
3. Quantum vs. classical transport (1 week)
   - Boltzmann Equation
   - length scales
   - ballistic transport
   - phase coherence
4. Fabrication and characterization techniques of nanoscale building blocks (1 week)
   - e-beam, AFM, STM, dip-pen, nanoimprint, self-assembly
   - materials and device characterization, TEM, AFM, SEM, SPM

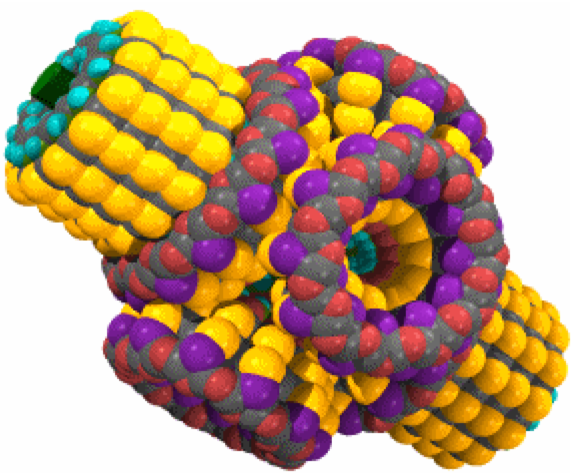
Schedule

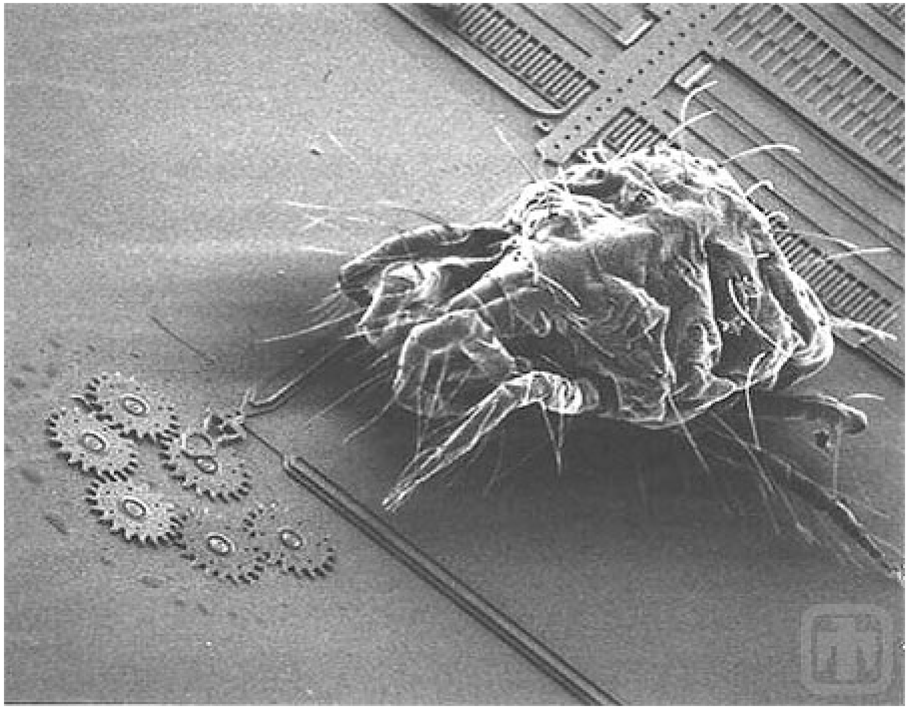
5. Single electron devices (2 weeks)
   - Coulomb blockade
   - superconducting SET
   - logic and memory applications
   - quantum cellular automata
6. Carbon nanotubes (2.5 weeks)
   - material structure and properties
   - low-T electrical properties
   - room-T properties and applications
     - FET, inverter, oscillator, optics, emitters, chemical sensors
     - NEMS
7. Semiconductor nanowires (2.5 weeks)
   - growth, heterostructures/band structure engineering
   - low-T electrical properties
   - room-T applications
     - FET, oscillators, assembly, biosensors
     - Environmental sensors, solar cells
     - Optics, lasers, NVMs, NEMS

Schedule

8. Molecular electronics (1 week)
    - single molecule devices
        - FET
        - memory devices
9. Spintronics (1 week)
        - spin-FET, coherent spin transport
        - spin valves and MRAM
10. Quantum computing (1 week)
        - qubits
        - entanglement and logic operation

What is nanotechnology?





Courtesy Sandia National Laboratories,
SUMMiTTM Technologies,
www.mems.sandia.gov

More than nanomachines and nanorobots

What is nanotechnology?

Nanotechnology comprises technological developments on the nanometer scale, usually 0.1 to 100 nm.

From Wikipedia, the free encyclopedia.

Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications.

The National Nanotechnology Initiative

Nanotechnology

↙ ↘

nanomaterials nanodevices

Nanomaterials

Catalysts - Enhanced surface area
- large number of active at corners and edges

-Platinum Group Metal Catalysts are $10-12 billion annually.

-Environmental waste management

-Hydrogen based energy

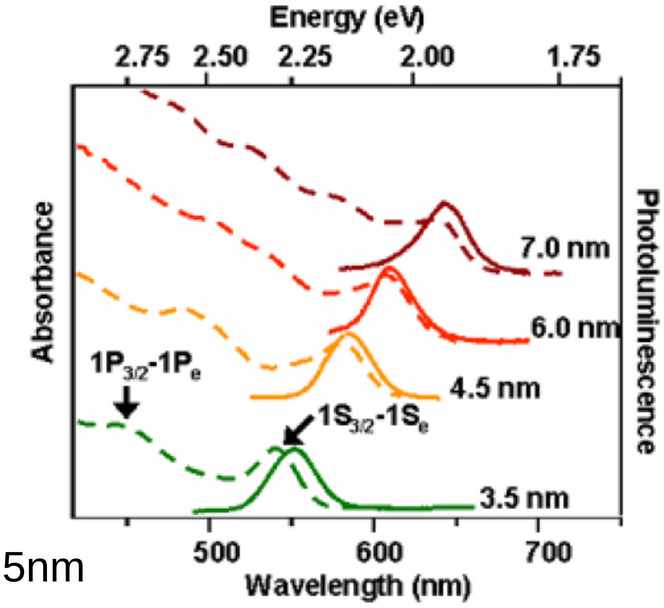
- -Fuel cells
- -Hydrogen storage

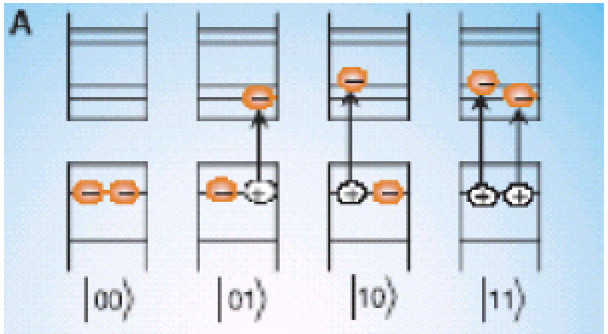
Not the emphasis of this course

Nanomaterials – Quantum size effects

CdSe nanoparticles
(quantum dots)

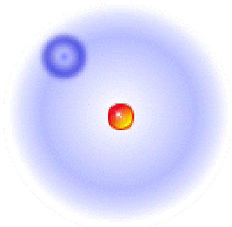
$E=h*f$





excitons

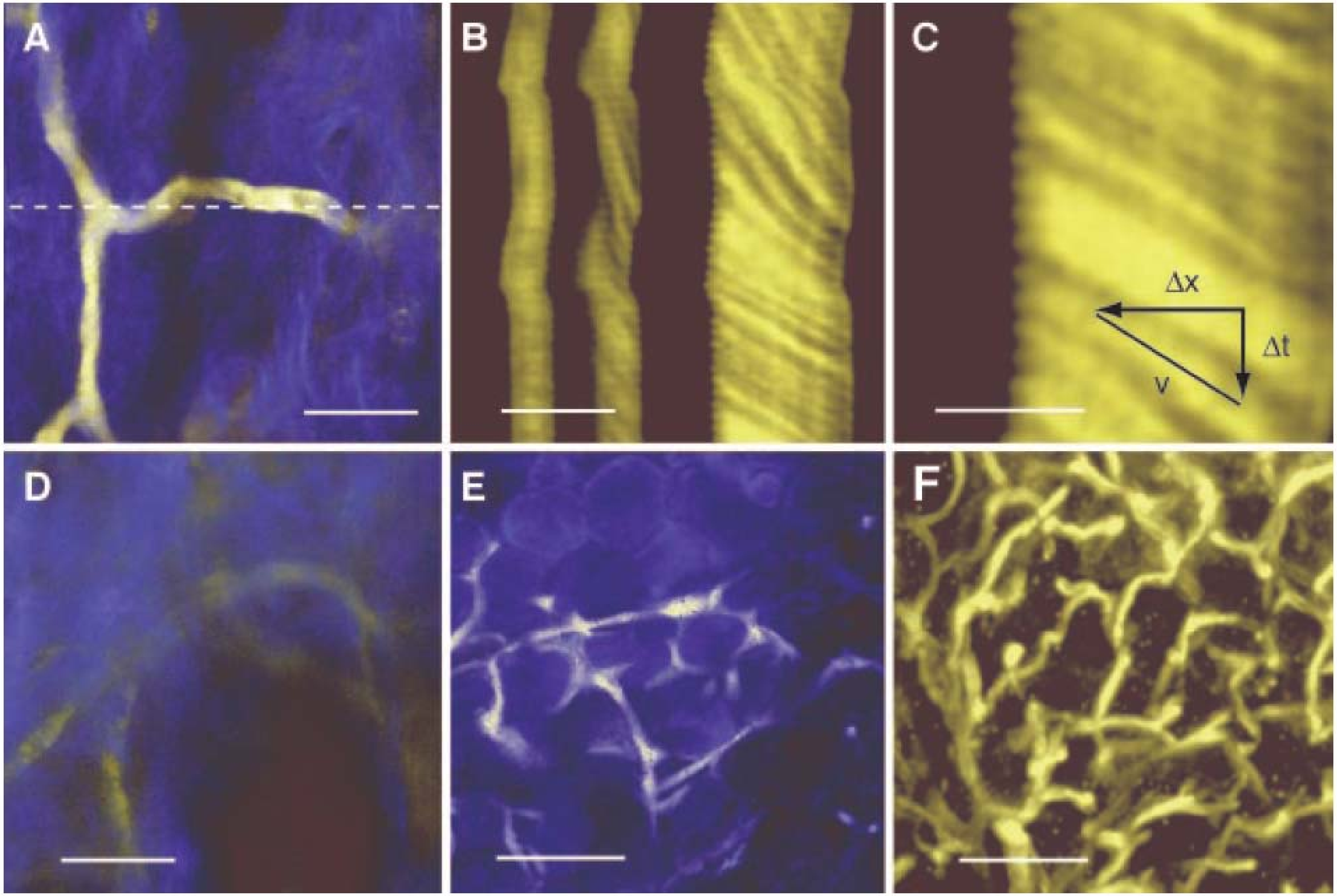
Hydrogen Atom



Exciton Bohr radius a_B~5.0-5.5nm

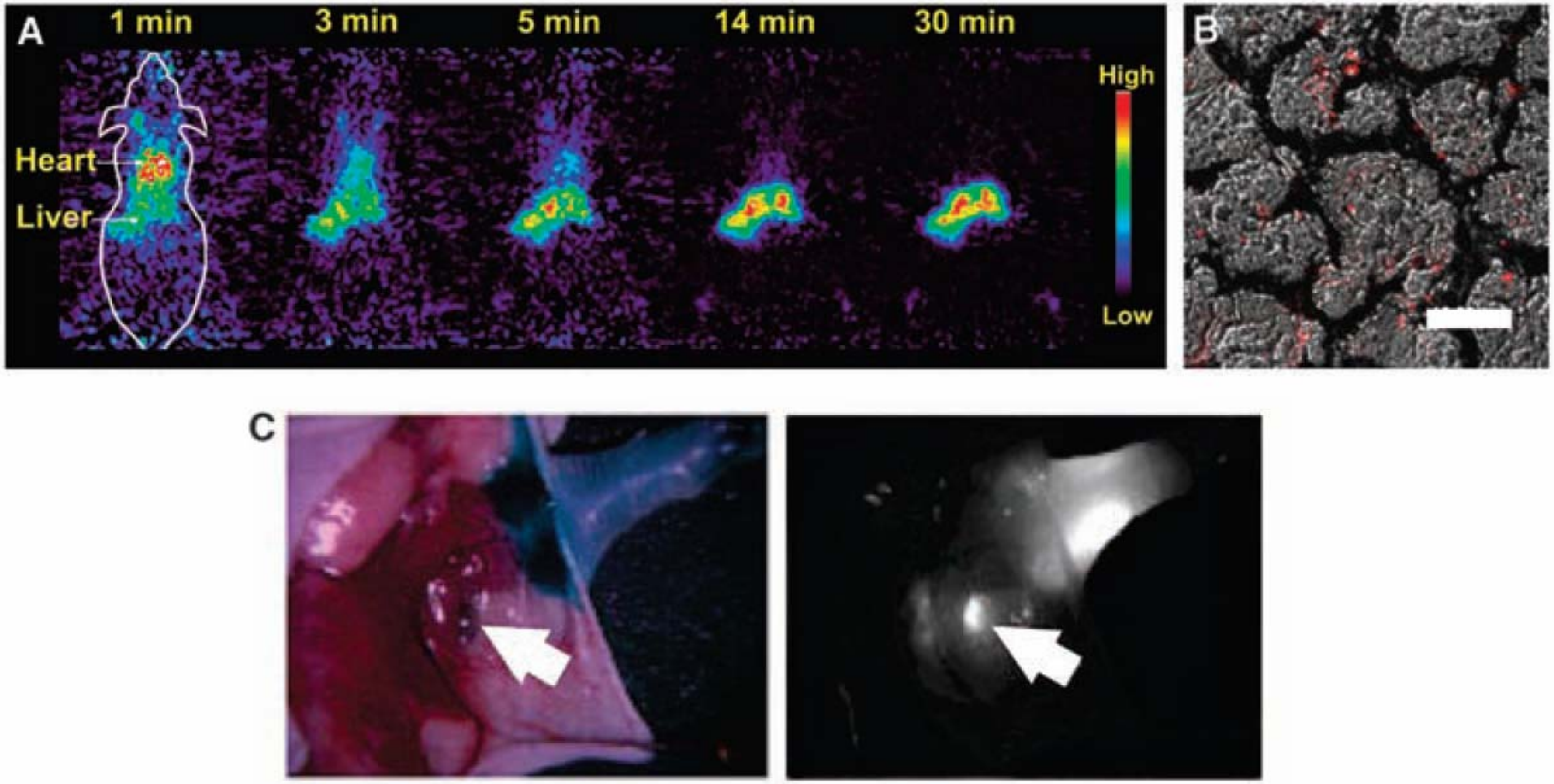
$$\Delta E_{1S_{3/2}-1S_e}(R) = E_{gap} + \left(\frac{h^2}{8\mu_{e,h}}\right)\frac{1}{R^2} - \left(\frac{e^2}{4\pi\varepsilon_0\varepsilon}\right)\frac{1}{R} + Smaller\ \ Terms\ (R)$$

Nanoparticles - bioimaging



Science, **300**, 1434 (2003)

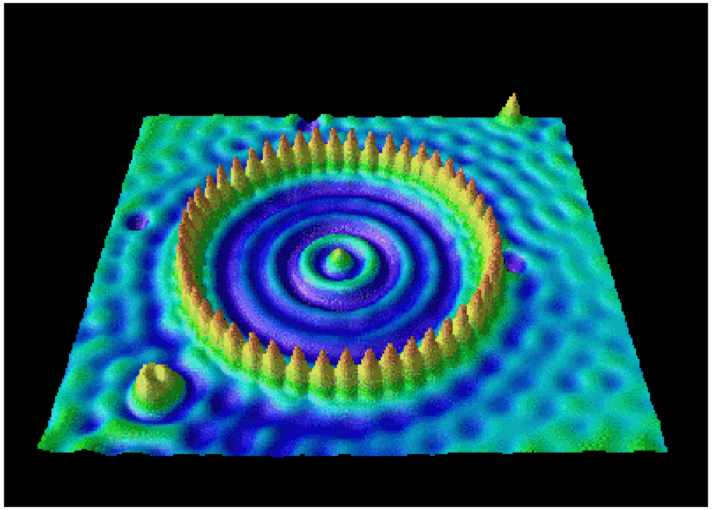
Nanoparticles - bioimaging



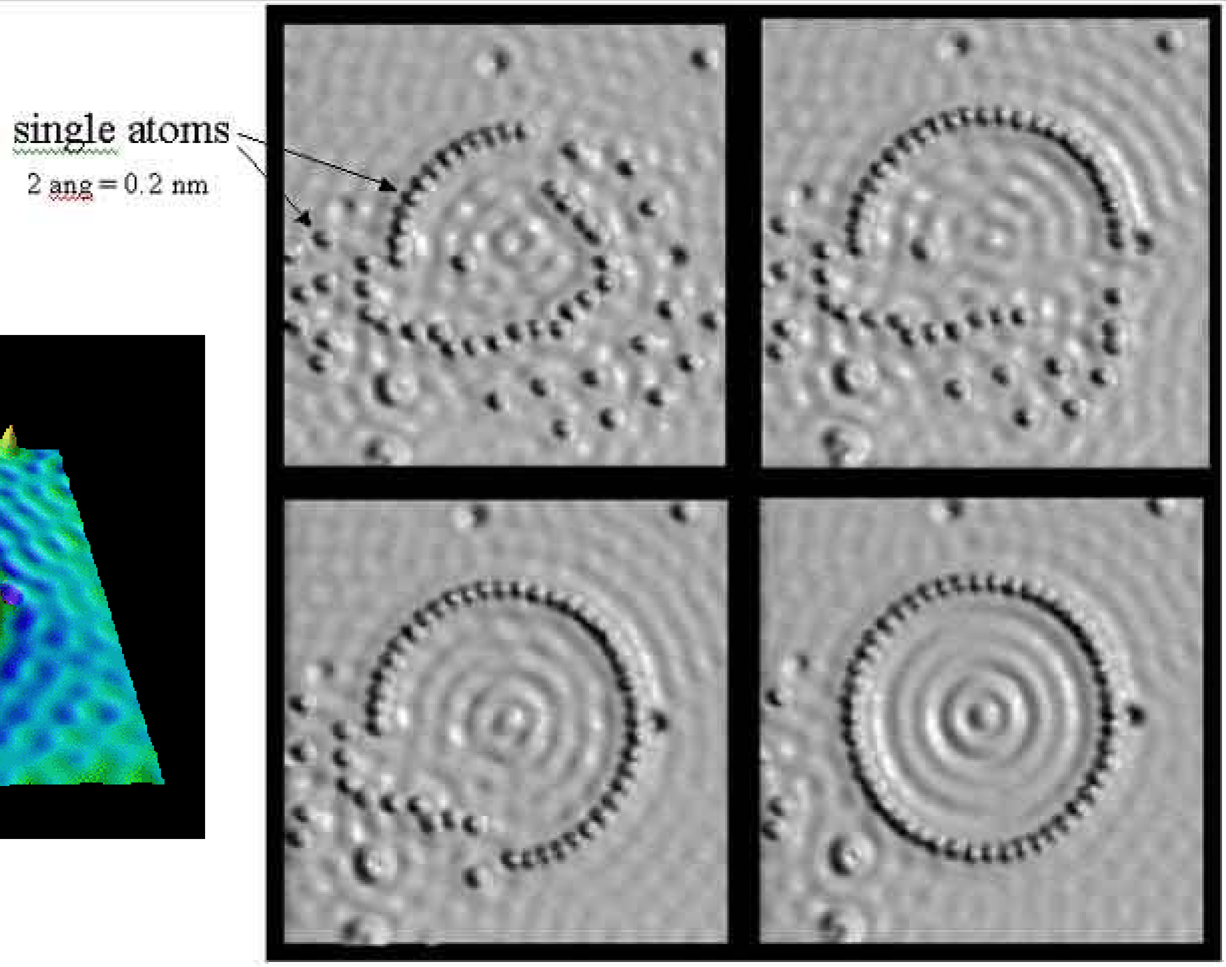
Drug delivery, etc

Science, **307**, 538 (2005)

Quantum corral



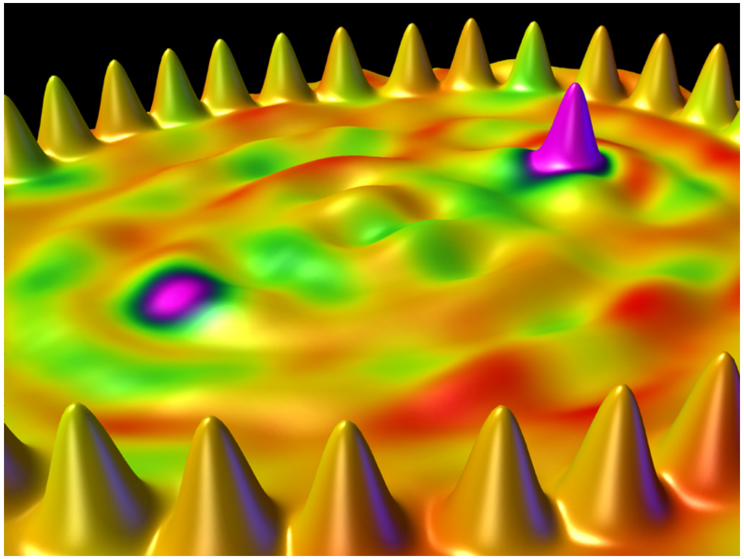
Standing waves of surface electrons



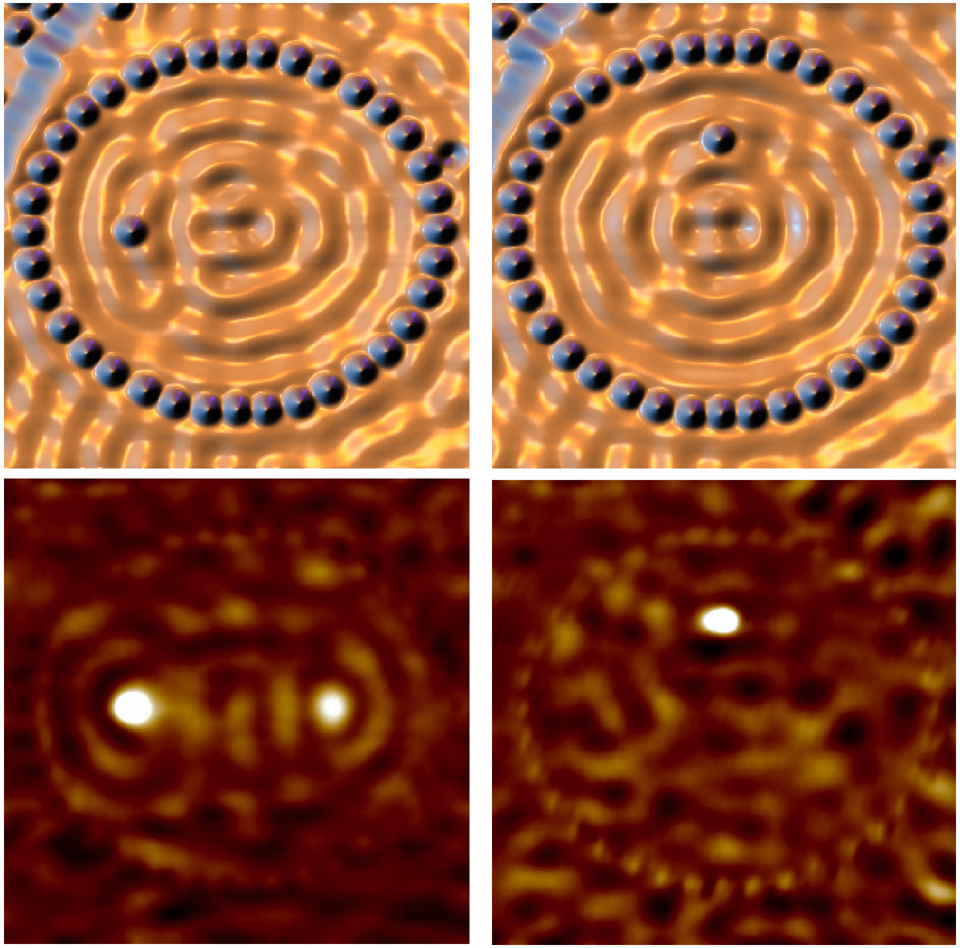
Xe atoms on Cu surface

Eigler group, IBM

Quantum mirage



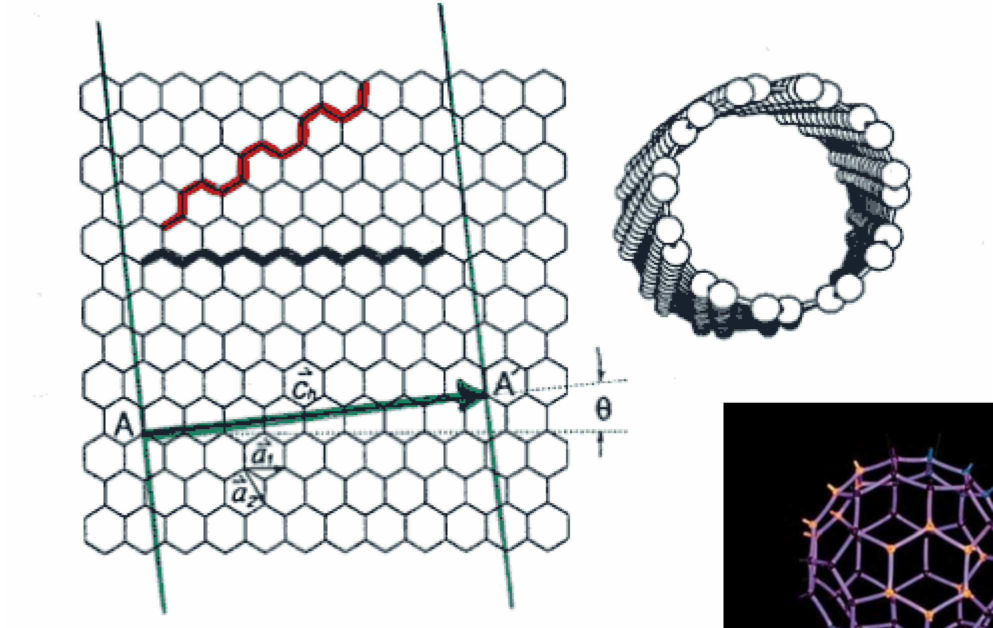
Co atoms on Cu surface

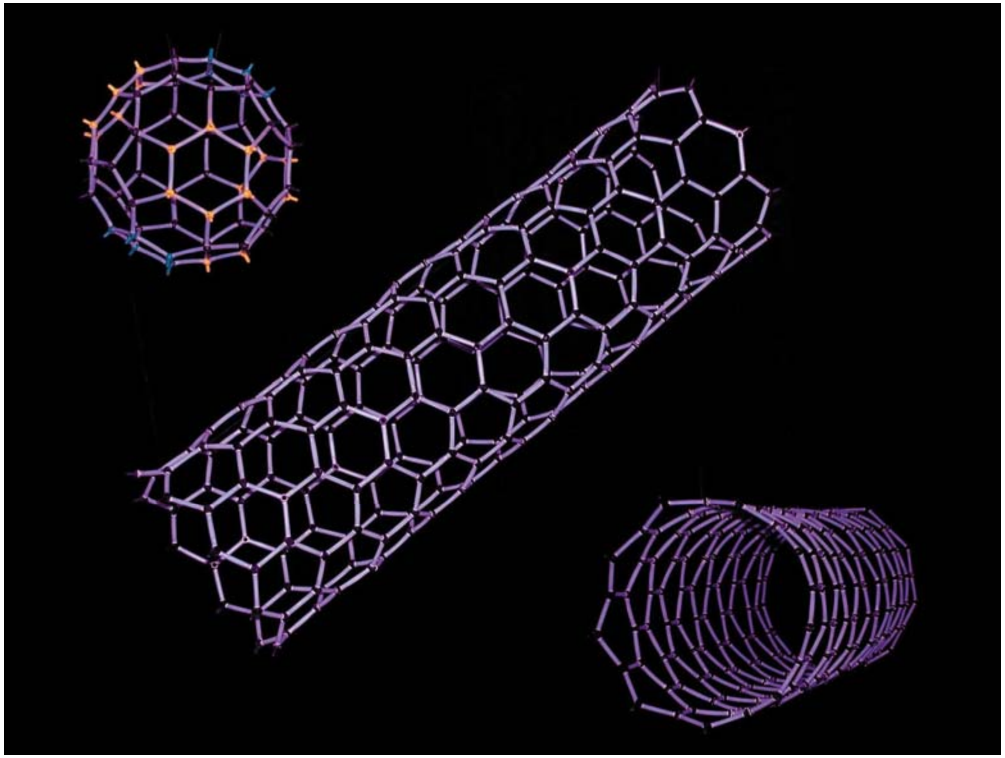


Eigler group, IBM

Information transferred by electron waves, similar to light/sound waves

Carbon Nanotubes





rolled-up graphene sheet

graphene: a single layer of graphite

Carbon Nanotubes

Field emission

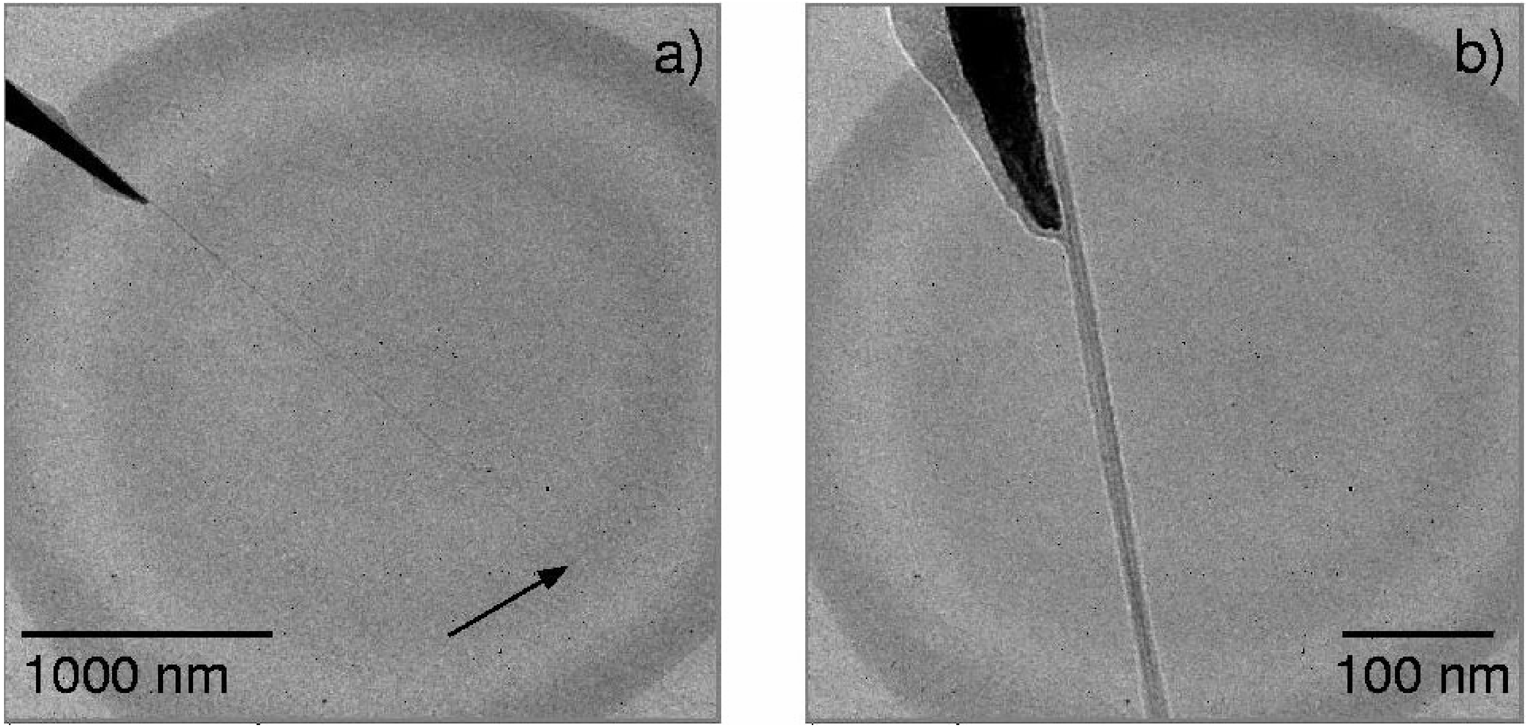
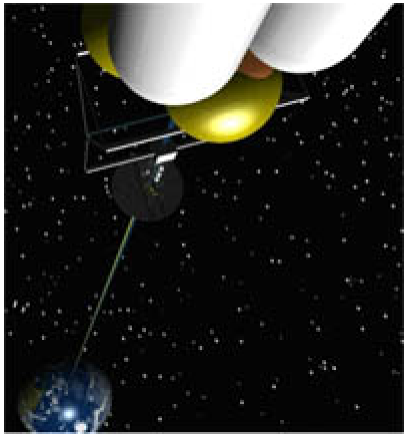
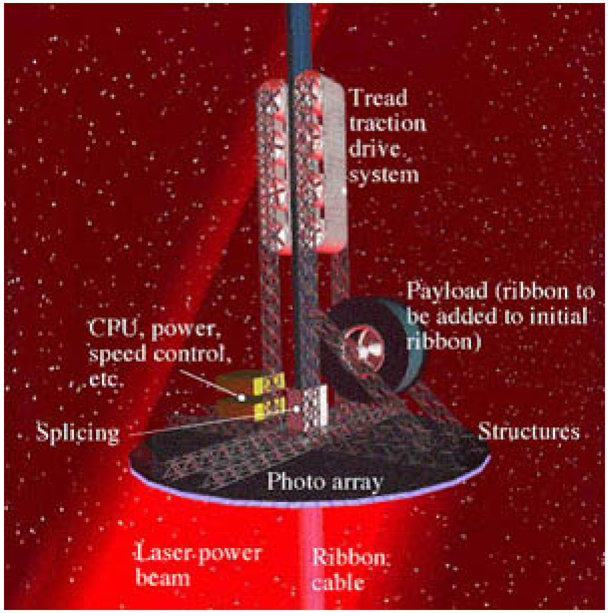


Image of CNT as SEM tips

Carbon Nanotubes

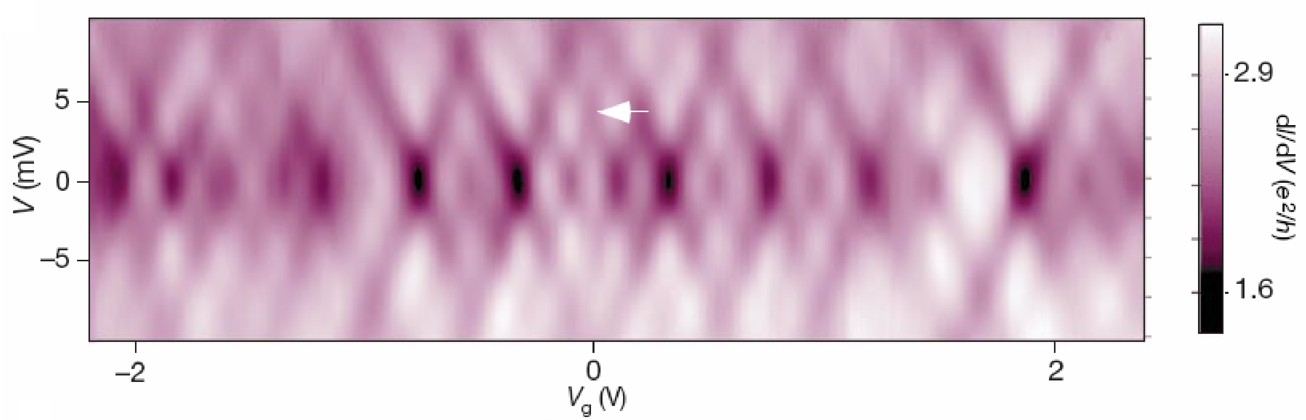
Excellent mechanical properties
hundreds of times stronger than steel. One nanotube string about half the diameter of a pencil is able to support 20 full-size cars (40,000 kilograms).



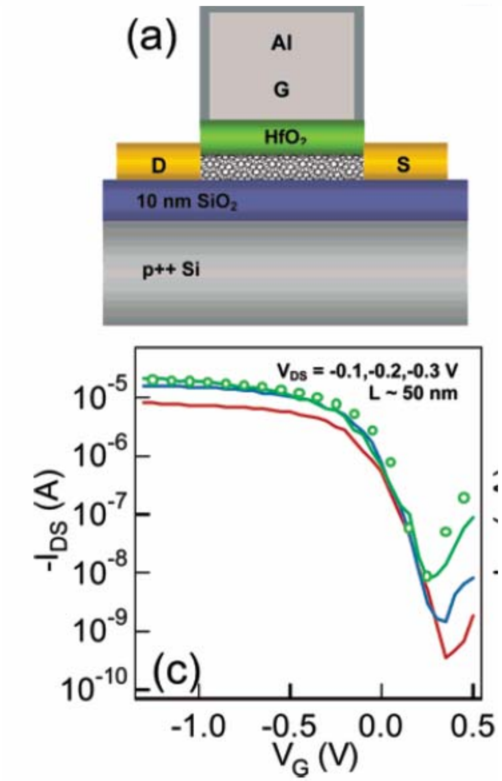


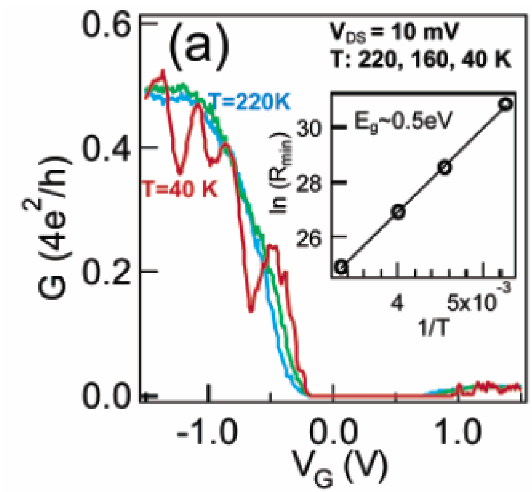
The space elevator

Carbon Nanotube devices



W. Liang, *Nature* **411**, 665 (2001)

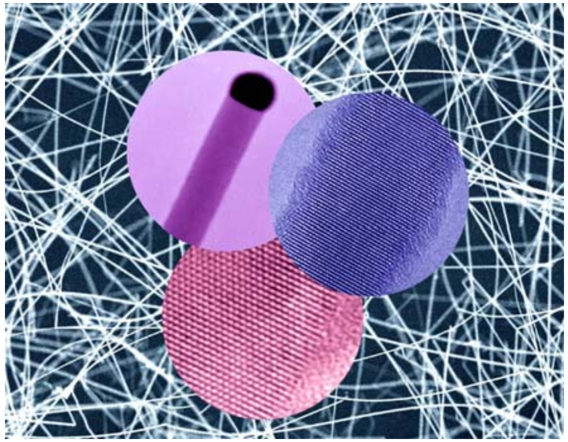


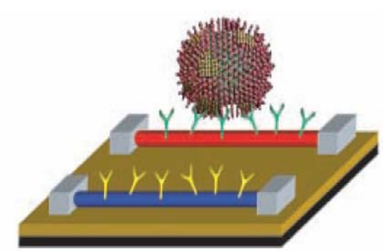


A. Javey *Nano Lett* **4**, 1319 (2004)

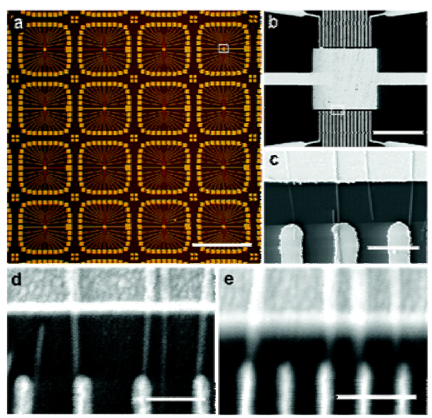
Single-crystalline Semiconductor Nanowires

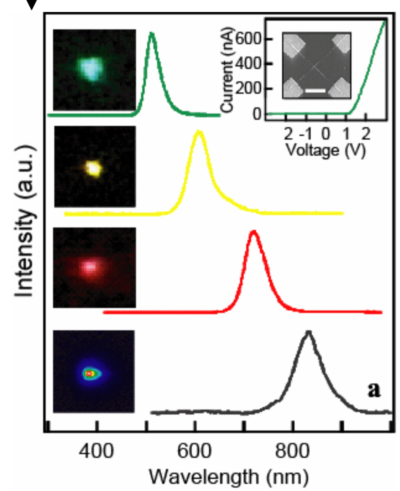
$d \sim 10$ nm
$L \sim 20$ μm

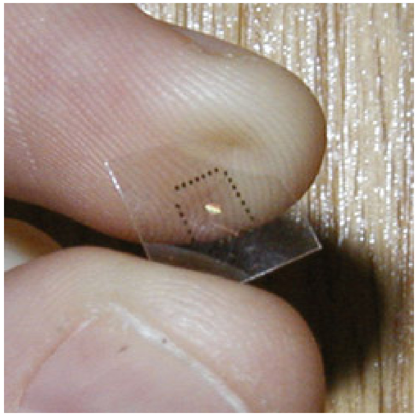




Single virus detection







Bio-sensing

Electronics

Photonics

Flexible devices

Nanodevices

The development and use of devices that have a size of only a few nanometers

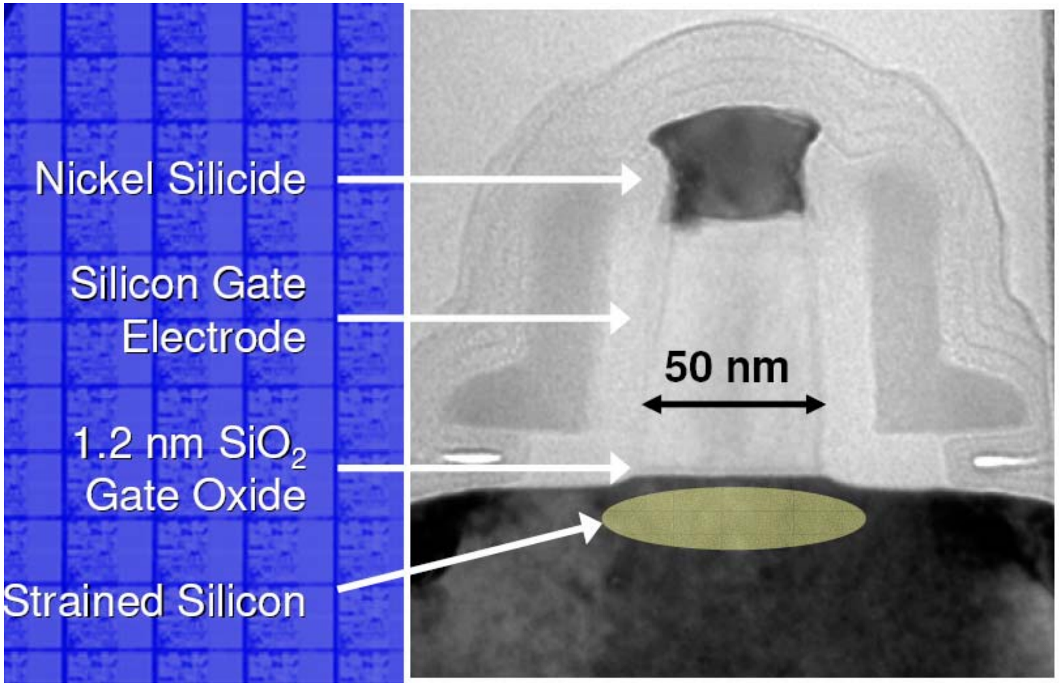
Device size, <100 nm

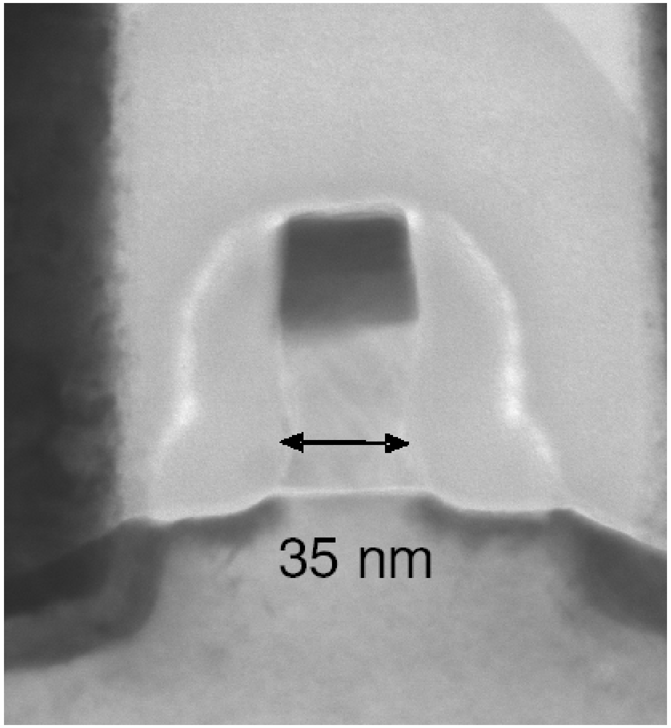
Current carried by only a small number of electrons

Device properties governed by quantum effects

} New device physics and device structures

Nanodevices



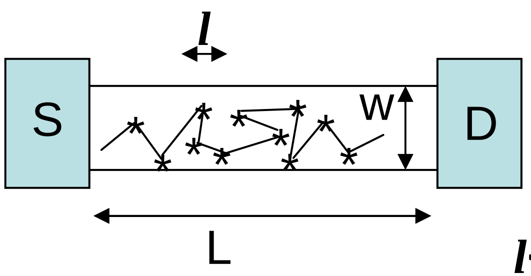


90 nm generation transistors

65 nm generation transistors

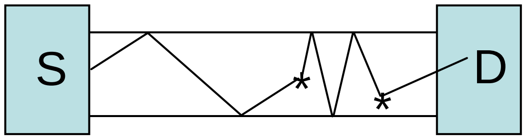
covered in EECS528

Ballistic transport



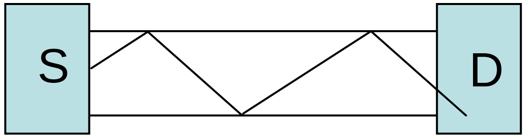
l<w,L, diffusive

Drude model. Device properties determined by *L*/***l*** independent sections



w<***l***<L, quasi-ballistic

Both boundary scattering and impurity scattering important

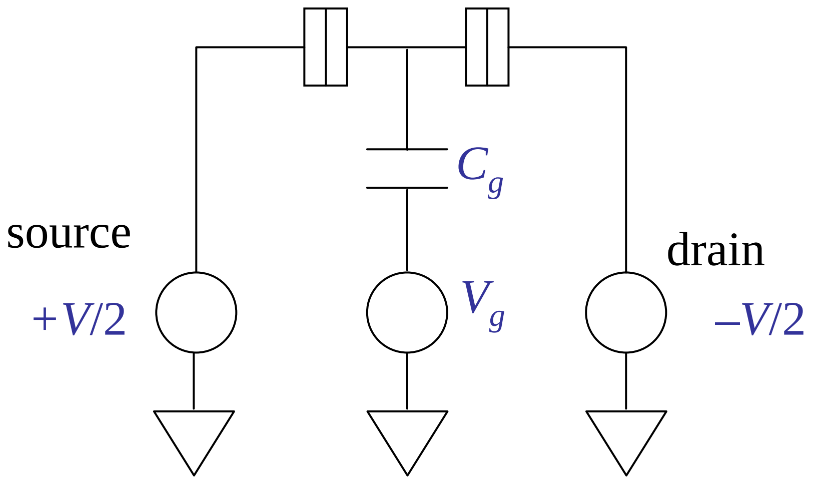


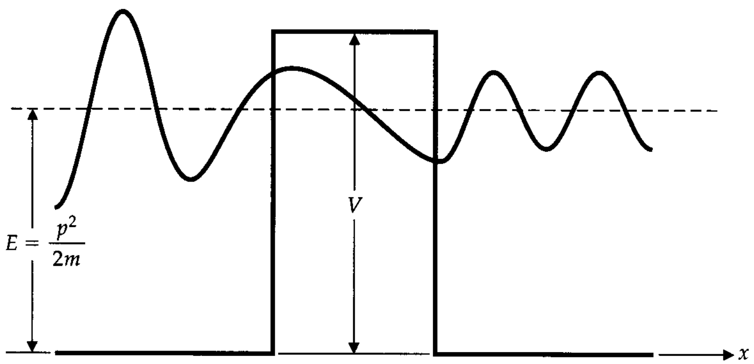
l>L, ballistic

Conductance doesn't depend on L
"no resistance", ultimate conductor
no scattering, -> no heat dissipation

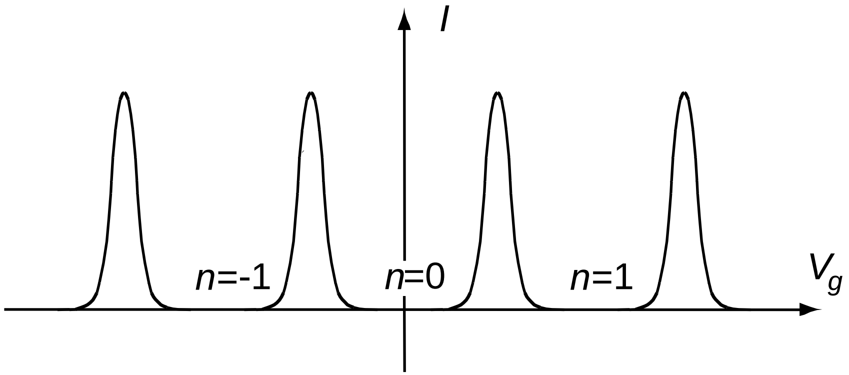
Current carried by only a small number of electrons

Single-electron transistor





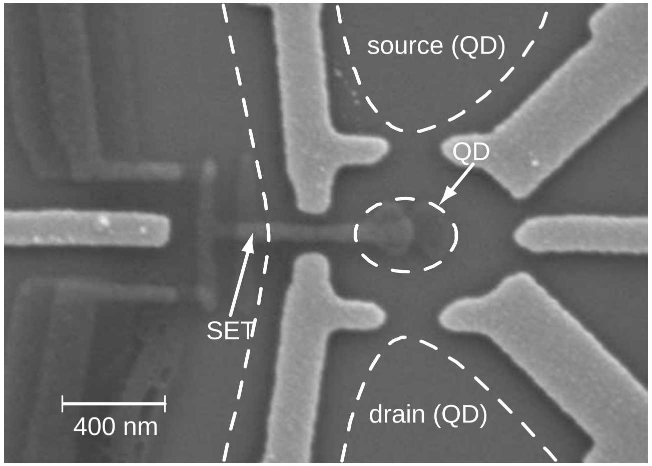
Tunneling of electrons

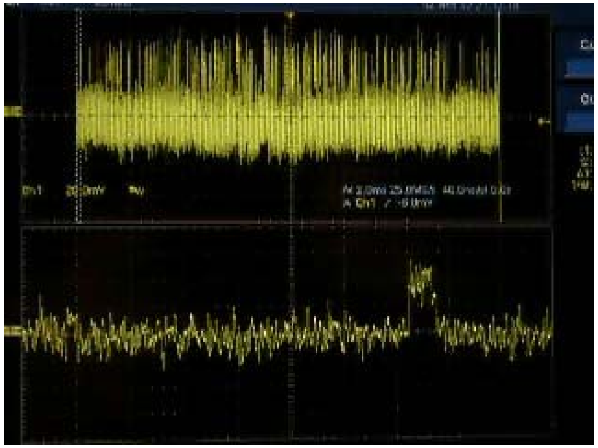


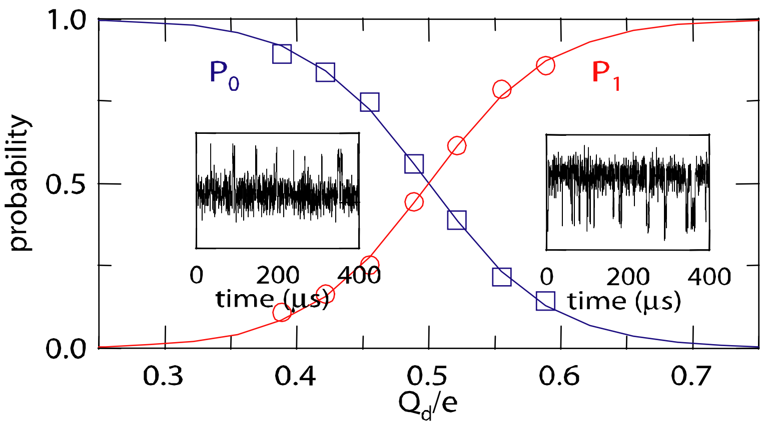
Energy cost to add an extra electron ~ e^2/C !

Coulomb blockade oscillations

Sensing the motion of individual electrons





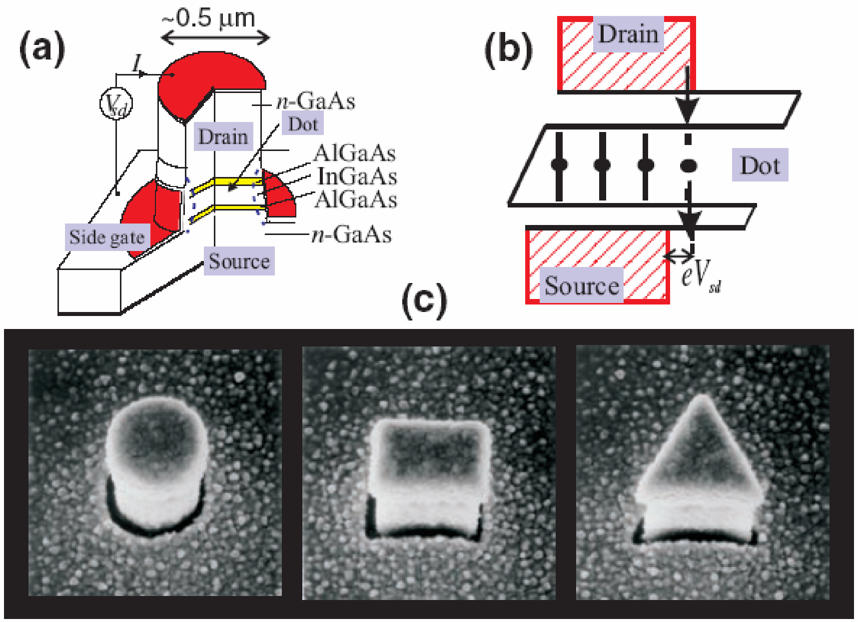


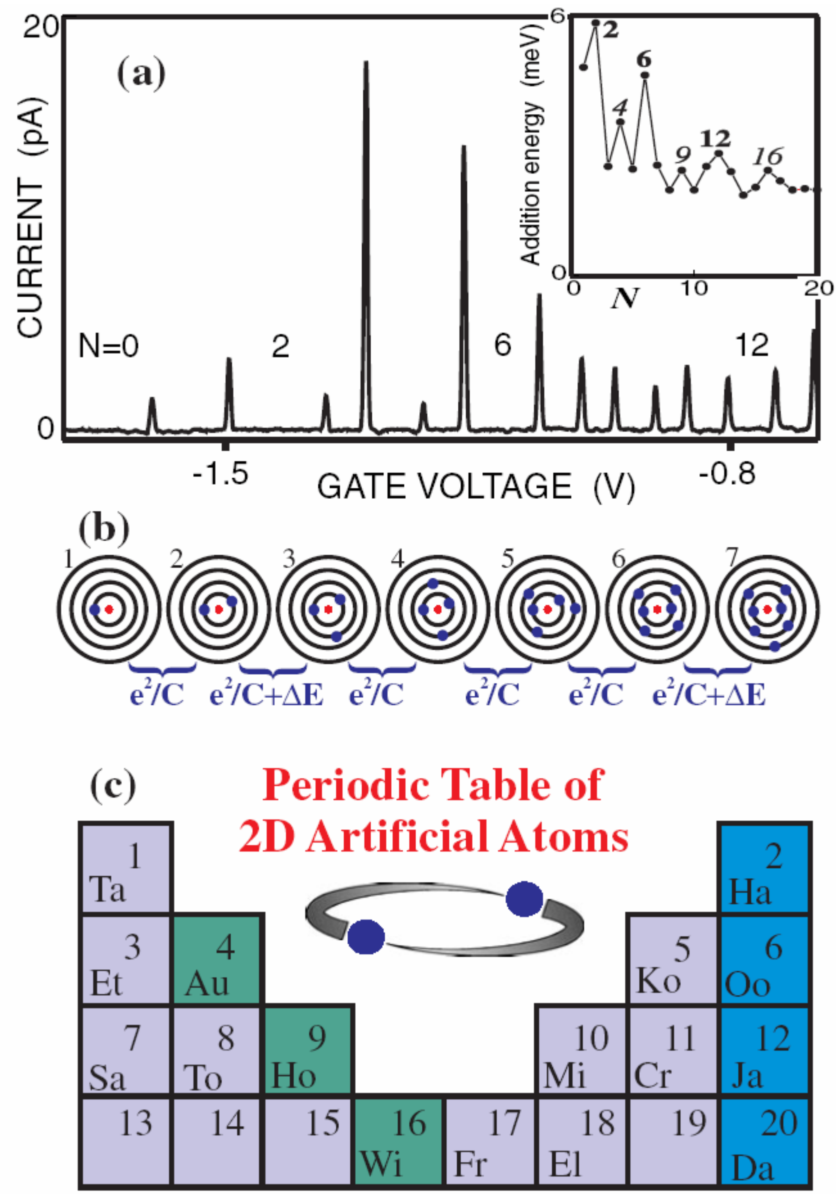
RF-SET coupled to a quantum dot (device under test)

W. Lu, Nature, **423**, 422 (2003)

Quantum size effects

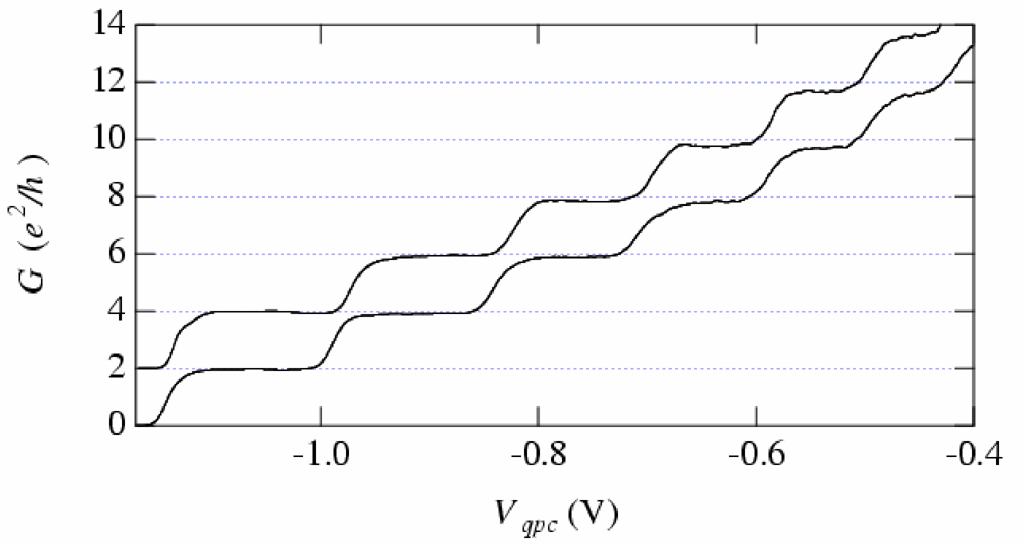
Semiconductor quantum dots
(artificial atoms)

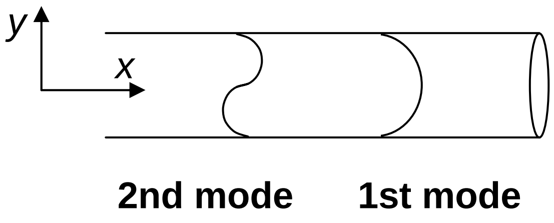




Kowenhoven, Rep. Prog. Phys. **64** (2001)

Quantized conductance

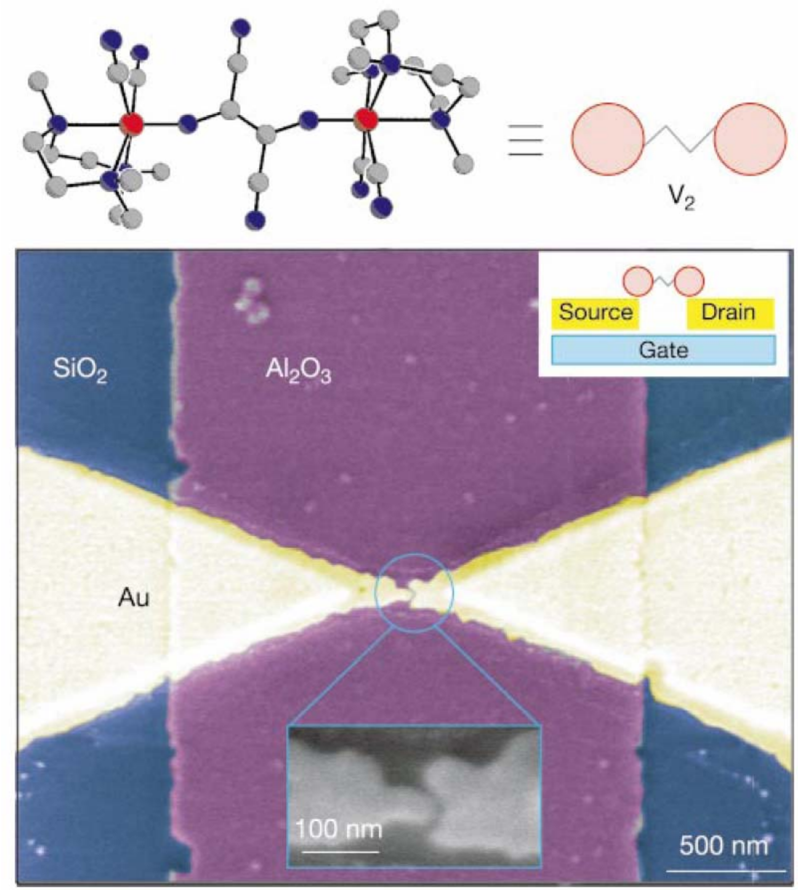


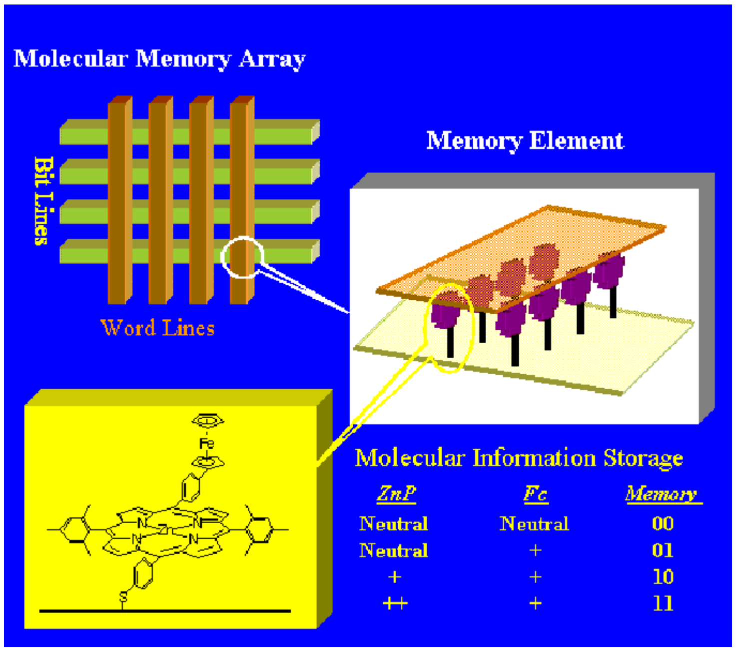


# of modes $n = \frac{k_y w}{\pi}$

Quantum size effects due to the wave nature of electrons!

Molecular Electronics

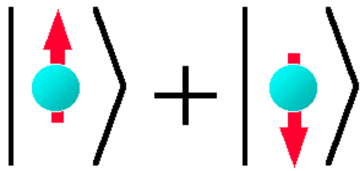




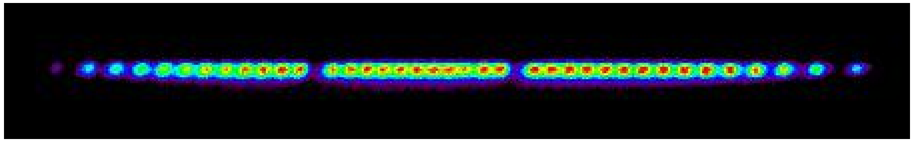
Single-molecule devices

Molecules as active medium

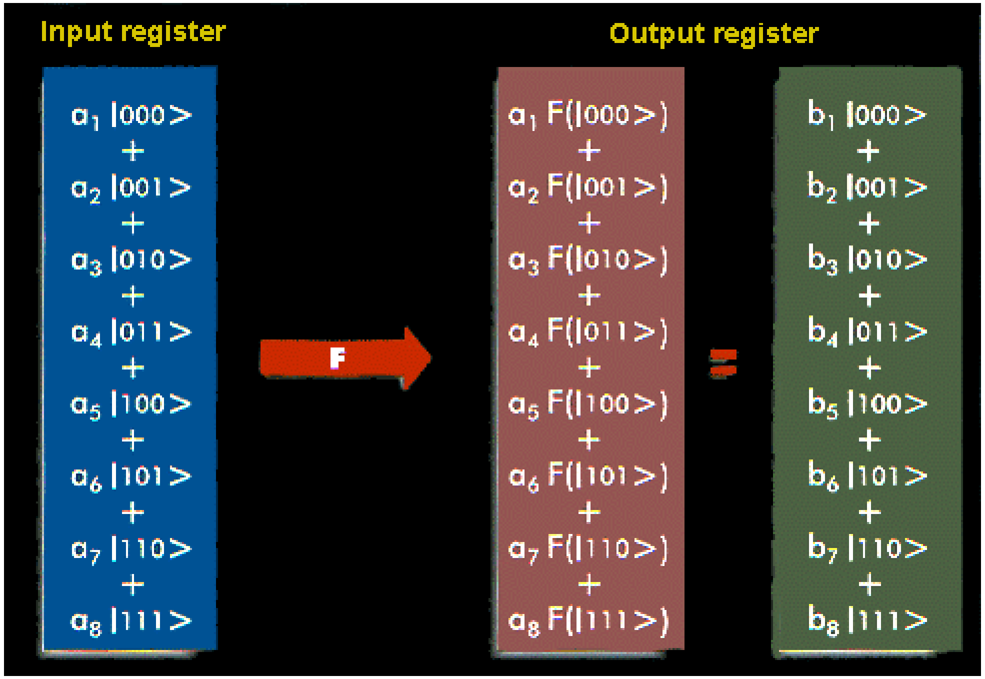
Quantum computation

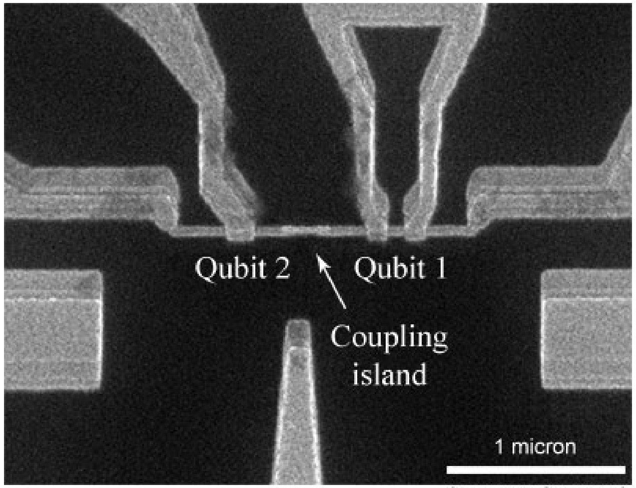


coherent superposition of 0 and 1



q-bits formed by atoms





Source: NEC Research

Solid state q-bits

There's plenty of room at the bottom

I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle…

What I want to talk about is the problem of manipulating and controlling things on a small scale.

As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market, they tell me, by which you can write the Lord's Prayer on the head of a pin. But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below...

Why cannot we write the entire 24 volumes of the Encyclopedia Brittanica on the head of a pin?

Richard P. Feynman

Dec 29, 1959