# Nanotechnology

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# 1st week

# Definition of Nanotechnology

- The Interagency Subcommittee on Nanoscale Science, Engineering and Technology (NSET) of the US Federal Office of Science and Technology Policy defines nanotechnology as: “Research and technology development at the atomic, molecular or macromolecular levels, devices and systems that have novel properties and functions because of their small and/or intermediate size. The novel and differentiating properties and functions are developed at a critical length scale of matter typically under 100 nm”.

- Royal Society of UK, “Nanotechnology is the production and application of structures, devices and systems by controlling shape and size at nanometer scale”.

# Nanoscales

- Nuclear scale: $10^{-15}$ m or $10^{-6}$ nm.
- Atomic scale: 0.1 nm or 1 angstrom (A).
- De Broglie wavelength in metals: ~1 nm.
- DNA molecules: 2 – 12 nm.
- De Broglie wavelength in semiconductors, mean free path in polycrystalline metal fils: 10 nm.
- Viruses: 10 – 100 nm.
- Nanostructures: less than 100 nm.

# Size ranges for different entities and devices

1 nm 10 nm 100 nm 1000 nm

STM SEM Optical Microscope

Nanotube

Virus

Bacteria

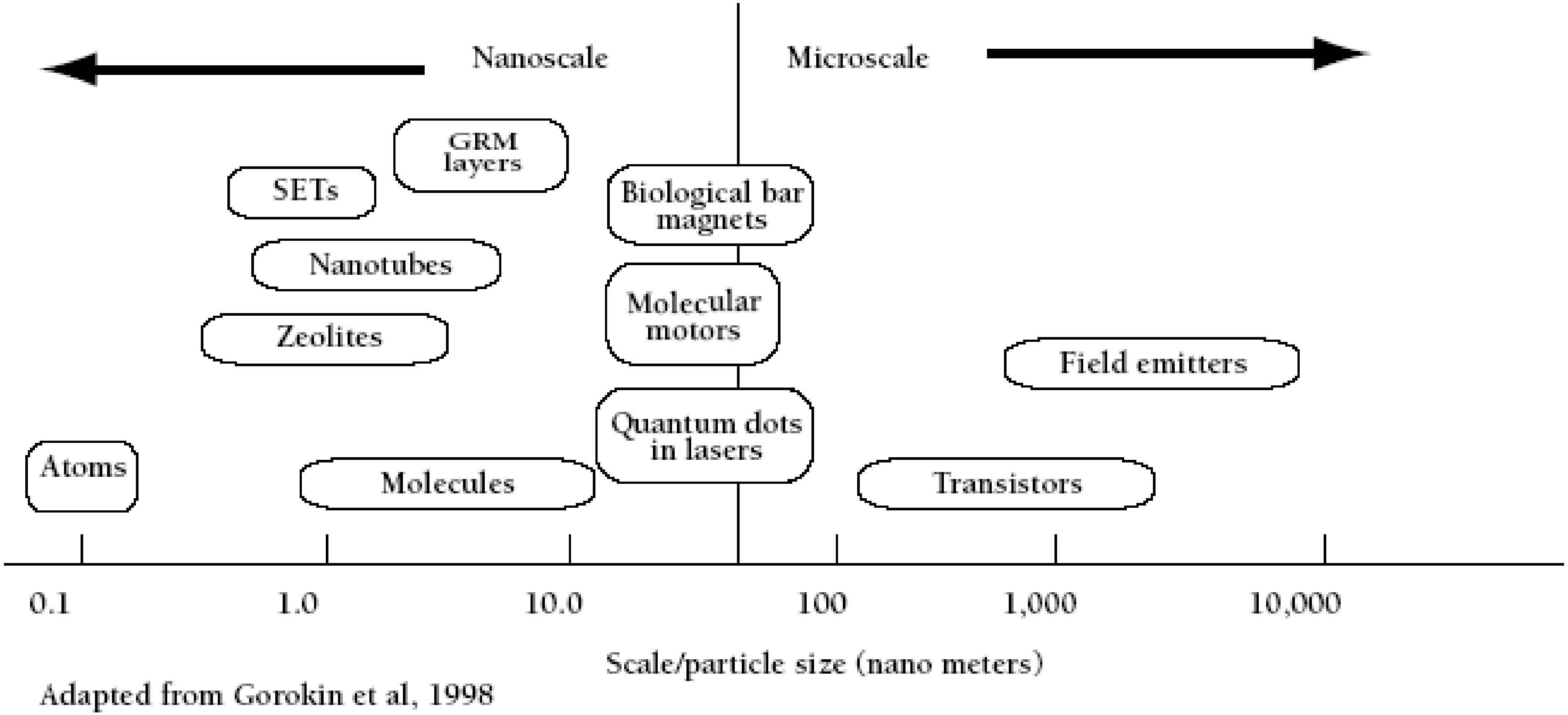
GMR layers

SET

Quantum dot laser

Red Blood Cell

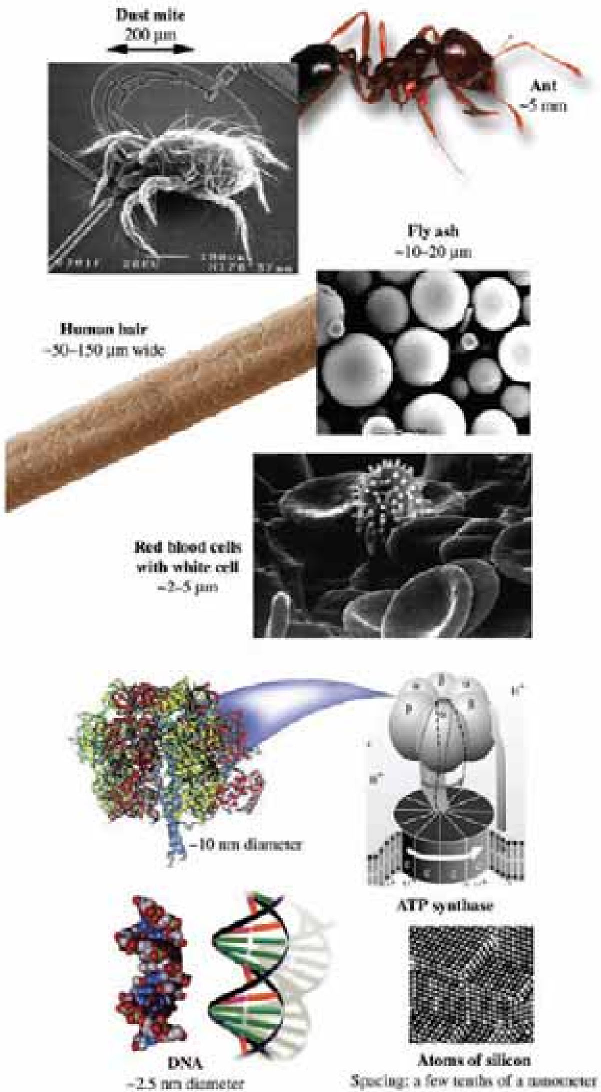
Fig. 2 Scale of some nano-scale products and applications.



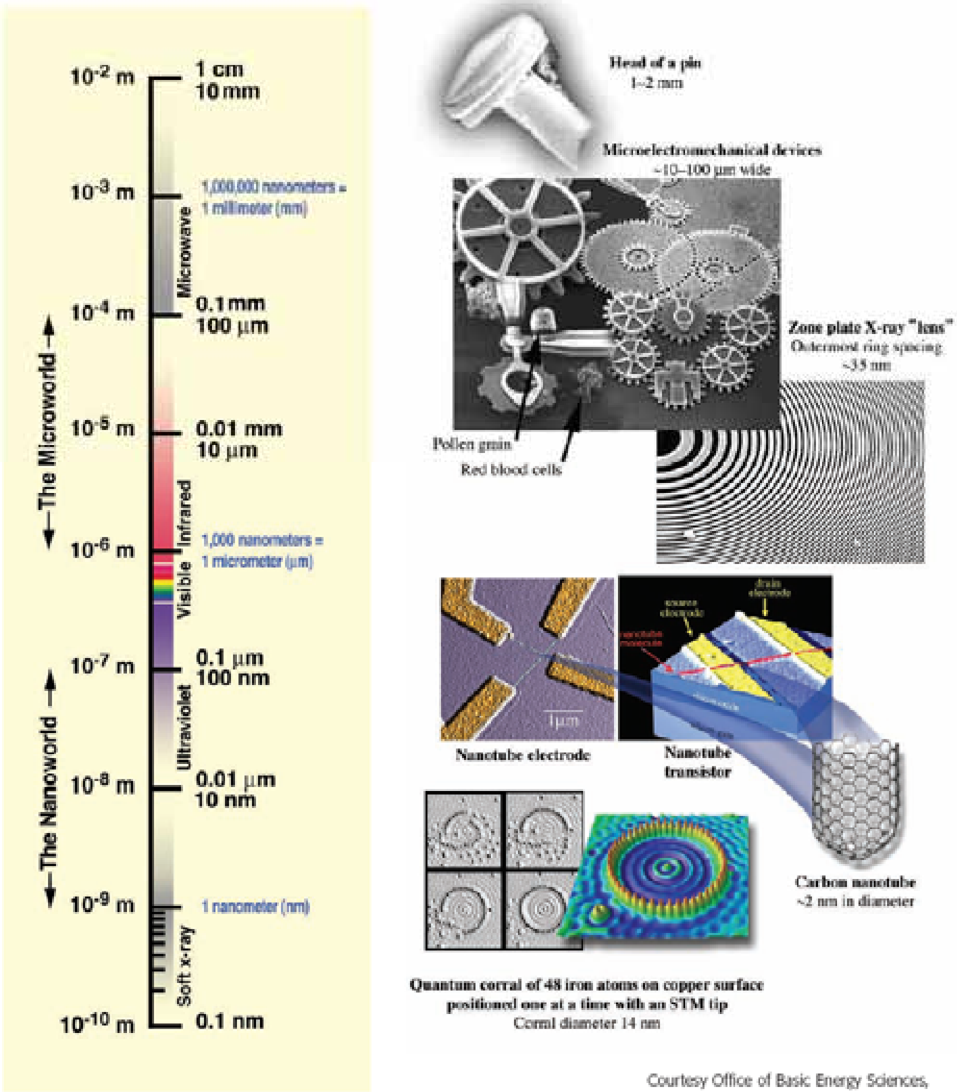
# *the* Scale of Things....

## *Nanometers & More*

## *things* Natural

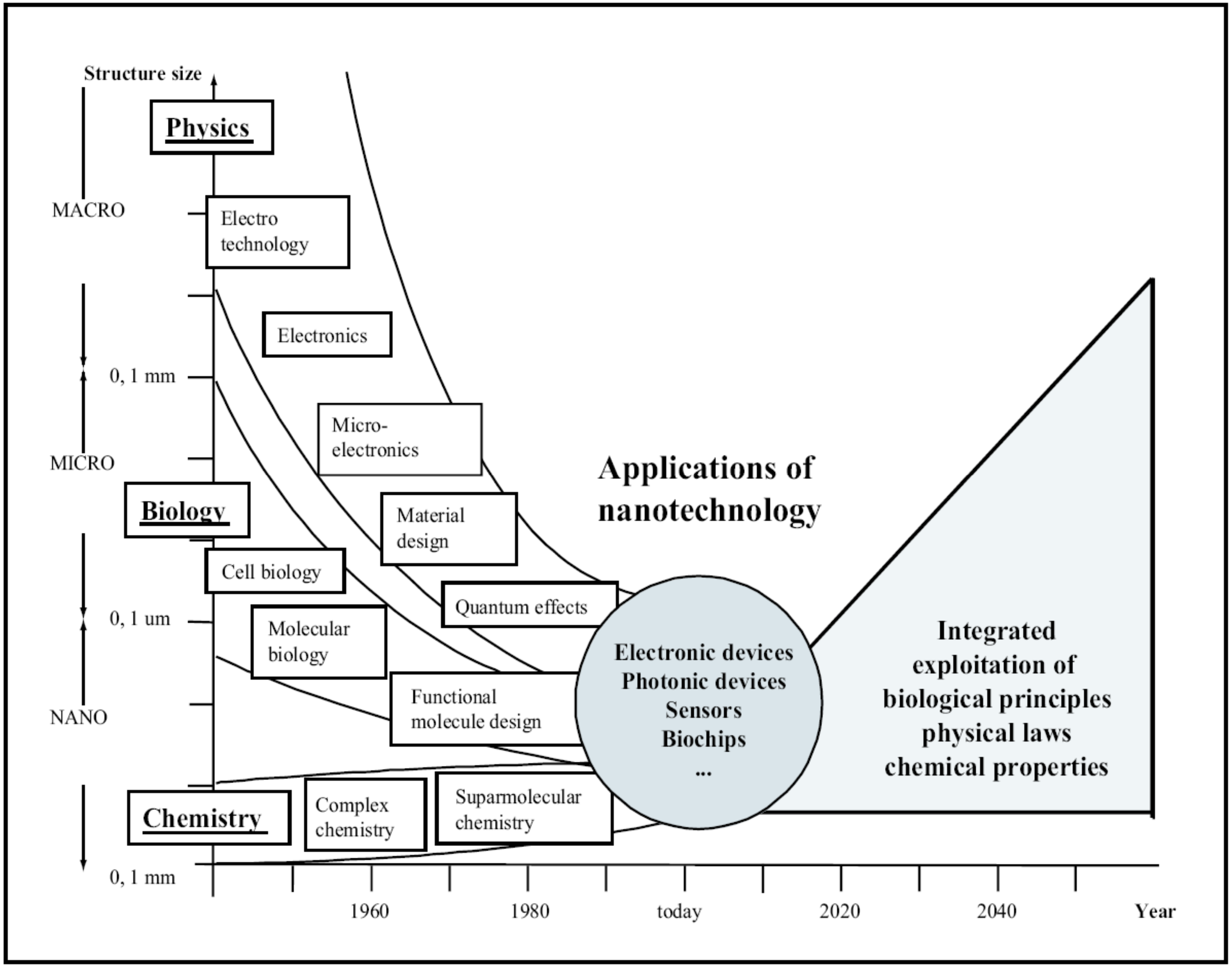


# *things* Manmade



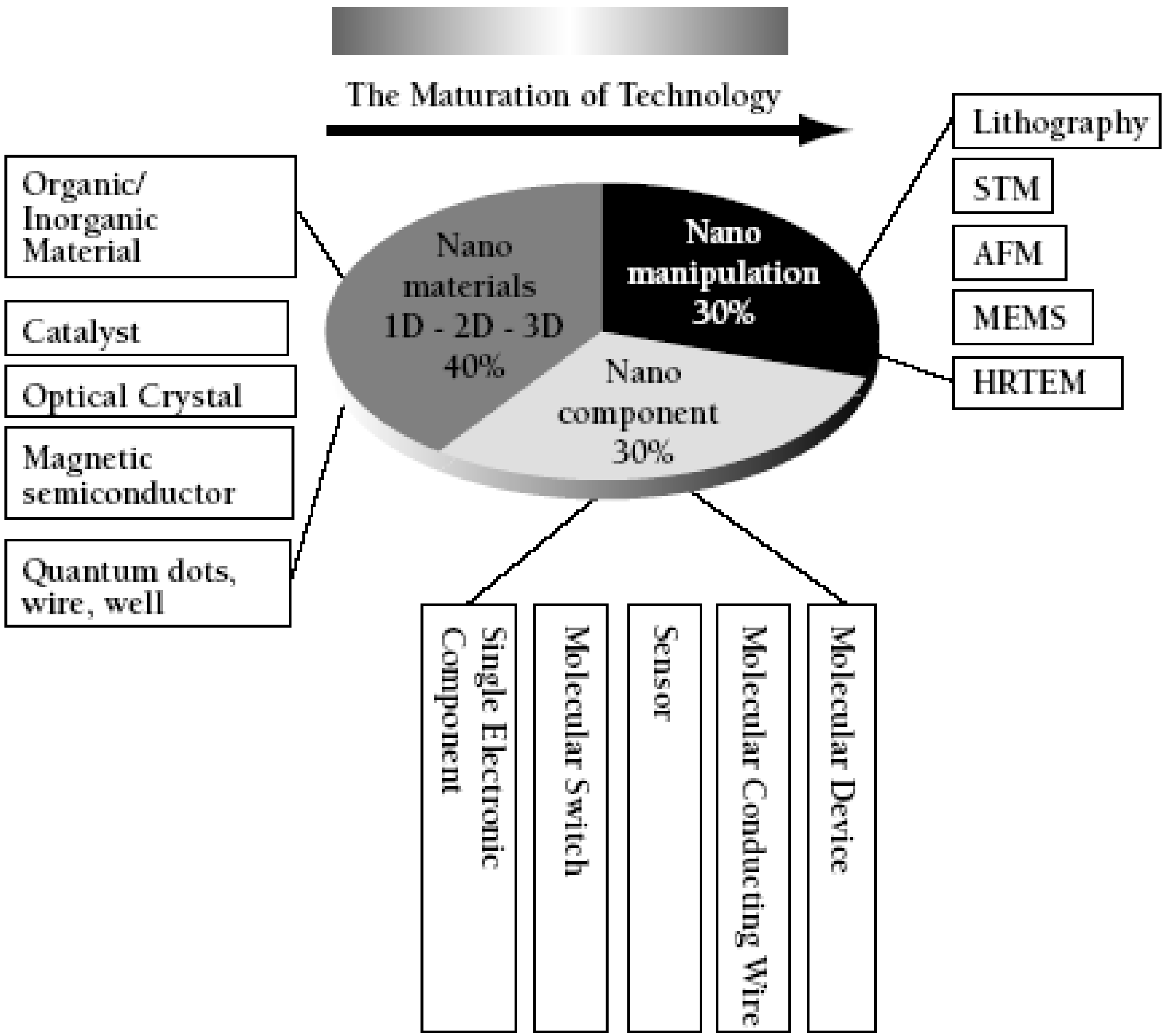

Courtesy Office of Basic Energy Sciences,
Office of Science, U.S. Department of Energy

Fig. 1 Physics, biology and chemistry meet in nanotechnology.




*Source: VDI-Technology Center, Future Technologies Division*

Fig. 1 Nanotechnologies: Areas of application and level of maturity.




Source: Data provided by Prof. Chung-Yuan Mou, Department of Chemistry, National Taiwan University.

Table 3. Nanostructured materials: properties and potential applications

| Property | Application |
|---|---|
| **Mechanical properties**<br>• High hardness and strength<br>• Superplastic behavior of ceramics<br>• Ductile ceramics | • Reinforcement fiber for high-strength composite<br>• Pure and composite high-strength fiber |
| **Thermal properties**<br>• Small heat capacity<br>• Lower sintering temperature | • Heat-exchange materials<br>• Combustion catalysts<br>• Sintering accelerators |
| **Optical properties**<br>• High and selective optical absorption of metal particles<br>• Size small than wavelength | • Colors<br>• Filters<br>• Solar absorbers<br>• Photographic material<br>• Photovoltaic<br>• Phototropic material<br>• Light or heat absorbers |
| **Electrical properties**<br>Small mean free path of electrons in a solid | • Special conductors |
| **Magnetic properties**<br>• Single magnetic domain<br>• Giant Magneto-Resistance | • Magnetic recoding<br>• Highly sensitive sensors<br>• Read/write devices<br>• Anti-lock automobile devices |

**Table 4. Properties and future applications related to particle size and large surface area of nanoparticles.**

| | Property | Future application |
|---|---|---|
| Particle size | Single magnetic domain | Magnetic recording |
| | Smaller than wavelength of light | Colored glass |
| | Superfine agglomeration | Molecular filters |
| | Uniform mixture of components | New materials and coating |
| | Hindered propagation of lattice | Strong and hard metals |
| | Imperfections | Ductile ceramics at elevated |
| | Enhanced diffusional creep | temperature |
| Large surface area | Specific | Catalysis, sensors |
| | Small heat capacity | Heat-exchange materials |
| | Dye-sensitized | Solar cell |

## Appendix 3: Future Applications of Nanostructured Materials

| Area | Future applications |
|---|---|
| Energy technologies | - new types of solar, such as the Grätzel cells<br>- window layers in solar cells from nanostructured semi-condcutors<br>- high energy density (rechargeable) batteries<br>- smart windows based on the photochrome effect or electrical orientation<br>- better insulation materials<br>- nanostructured rocketfuel ignitors for longer-lasting satellites<br>- on-line repairable heat-exchangers in nuclear power plants<br>- magnetic refrigerators from superparamagnetic materials<br>- elimination of pollutants in power generation equipment |
| Automobile industry | - corrosion protection of an automobile's coach-work, stainless steel<br>- elimination of pollutants in catalytic converters<br>- electrical or hybrid cars using batteries based on nanostructured materials<br>- smart windows<br>- automobiles with greater fuel efficiency using nanostructured spark plugs and heat-resistant coatings for engine cylinders<br>- scratch-resistant top-coats of hybrid materials<br>- intrinsically simple couplings for automobile fabrication<br>- automobile engine performance sensor |

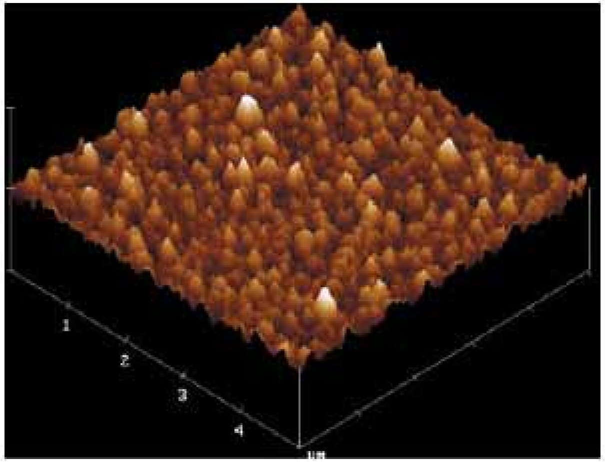
| | |
|---|---|
| Optics | - graded refractive index (GRIN) optics: special plastic lenses<br>- scratch-resistant plastic reading aids, lenses, visors, head lights and car windows<br>- anti-fogging coatings for spectacles and car windows<br>- cheap colored glass<br>- optical filters |
| Electronics: materials for the next-generation computer chips | - single-electron tunneling transistors using nanoparticles as quantum dots<br>- efficient electrical contacts for semiconductor devices<br>- electrically conducting nanoceramics<br>- conducting electrodes for photoconductors and solar cells<br>- capacitive materials for, e.g., dynamic random access memories (DRAM)<br>- magnetic memories based on materials with a high coercivity<br>- magnetorestrictive materials, important for shielding components and devices<br>- soft magnetic alloys such as Finemet<br>- resistors and varistors (voltage-dependent resistors) |

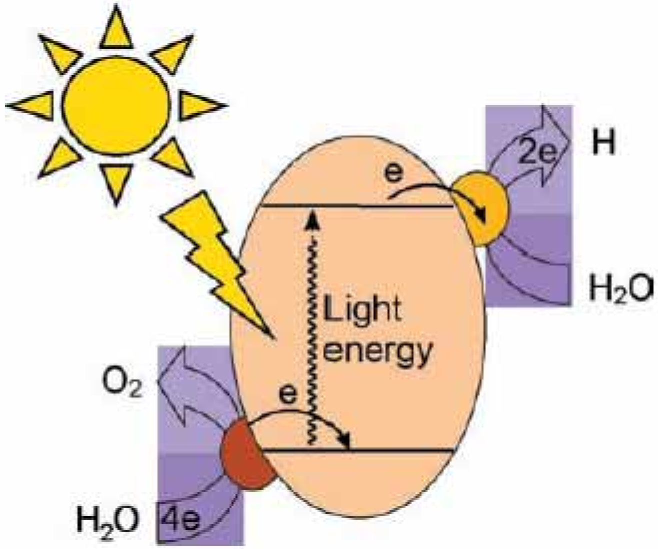
| | |
|---|---|
| Electronics: materials for the next-generation computer chips | - high-temperature superconductors using nanoparticles for flux pinning<br>- liquid magnetic O-rings to seal off computer disk drives<br>- ‘nanophosphors’for affordable high-definition television and flat panel displays<br>- electroluminescent nanocrystalline silicon, opening the way for optoelectronic chips and possibly a new type of color television |
| Optoelectronics | - efficient light-emitting diodes based on quantum dots with a voltage-controlled, tunable output color<br>- plastic lasers using nanoparticles as an active scattering medium<br>- optical switches and fibers based on nonlinear behavior<br>- transparent conducting layers<br>- three-dimensional optical memories |
| High-sensitivity sensors | - gas sensors for Nox, Sox, CO, CO2, CH4 and aromatic hydrocarbons<br>- UV sensors and robust optical sensors based on nanostructured silicon carbide (SiC)<br>- smoke detectors<br>- ice detectors on aircraft wings |

| | |
|---|---|
| Catalysis | - photocatalytic air and water purifiers<br>- better activity, selectivity and lifetime in chemical transformations and fuel cells<br>- precursors for a new type of catalyst (Cortex-catalysts)<br>- stereoselective catalysis using chiral modifiers on the surface of metal nanoparticles |
| Medical | - longer-lasting medical implan'ts of biocompatible nanostructured ceramics and carbides<br>- coatings for medical applications |
| | - tougher and harder cutting tools, especially based on nanocrystalline carbides<br>- high performance parts for the aerospace and the building industry<br>- gas-tight and dense metals<br>- fire protection coatings<br>- 20-nm-thin foil for food packaging<br>- thermoelectric materials (used for thermocouples)<br>- ceramic membranes for energy-efficient separation methods (for uranium, milk, malt beer etc.) |

| | | |
|---|---|---|
| Various other applications | - | 'self-lubricating' coatings based on diamond-like nanocomposites, to be used on sliding parts in the automotive, chemical, pharmaceutical, or biomedical industry |
| | - | easy-to-clean surfaces, for instrance anti-graffiti coatings for trains, glass walls and brick walls |
| | - | strong plasitc floors |
| | - | binder for natural fibers and core sand |
| | - | ferrofluids for mechanical vibration damping in stepper motors, magnetic muscles, dirt absorbers in waste separation facilities |
| | - | molecular filters |
| | - | fast-burning metal powders for the military |

# Scalable Methods to Split Water with Sunlight for Hydrogen Production



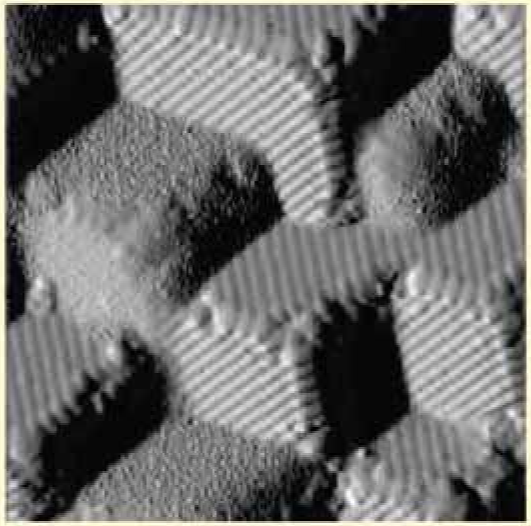


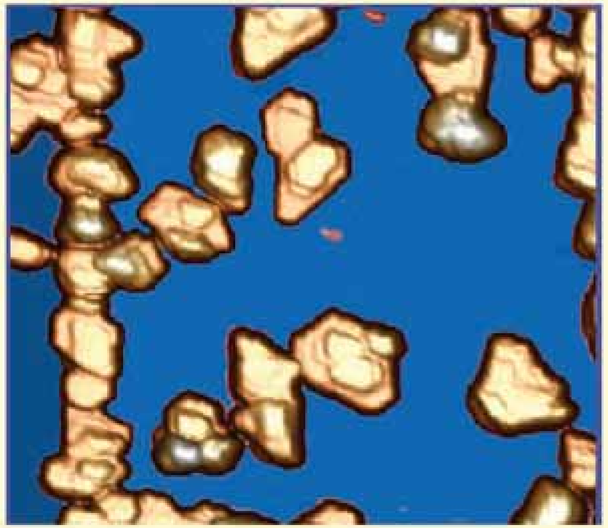

Left: Atomic force microscopy image of titanium dioxide photocatalysts for water splitting. Right: Schematic of the catalytic water splitting process (courtesy of T. Vogt, E. Fujita and J. Muckerman, Brookhaven National Laboratory).

### Producing Hydrogen with Sunlight

The energy challenges facing the world coupled with the concern of improving our environment require science and technologies for providing clean energy sources. A major step was taken by President Bush in the Administration's Hydrogen Fuel Initiative, which he unveiled in his State of the Union address in 2003. To achieve the envisioned hydrogen future, it is vital to develop methods for the clean production of hydrogen. A promising route is to use the energy of sunlight to split water into its constituent elements, oxygen and hydrogen. Honda and coworkers demonstrated that illuminating semiconductor catalysts such as titanium dioxide with ultraviolet light successfully split water to produce hydrogen. Major scientific challenges remain in developing this into a useable technology. The wavelength of light necessary for this process must be shifted away from the ultraviolet (~2% of sunlight) to the more plentiful visible range of sunlight. Promising results in this direction have been found based on tuning the size of the catalyst particles into the nanometer regime, as well as on the addition of nanoscale additives. Research results have shown indications that the addition of carbon to titanium dioxide may increase the conversion efficiency to about 8%, approaching the Department of Energy's 10% target for a commercially viable catalyst.

# Highly Selective Catalysts for Clean and Energy-efficient Manufacturing



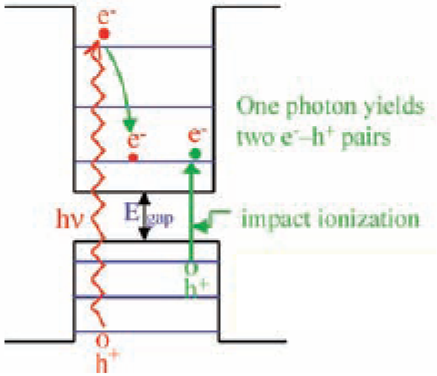


Left: STM image of faceted Pd/W(111) (15 nm x 15 nm)—Rows of individual atoms are visible on the flat faces of the three-dimensional nanoarchitecture of a faceted W surface. Right: STM image (200 nm x 200 nm)—Ruthenium nanoparticles on a graphite substrate (courtesy of T. Madey, Rutgers Univ., and J. Hrbek, Brookhaven National Laboratory).

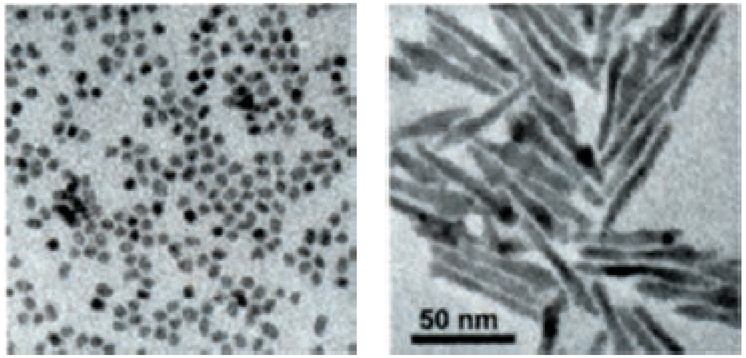
## Highly Selective Catalysts

Achieving a high degree of selectivity in catalysis is recognized as a crucial challenge for the coming decades. While nature attains 100% selectivity in nanometer-scale enzyme catalysts, such selectivity in synthetic systems remains an elusive goal. Nanoparticles and nanostructured materials offer new avenues of controlling catalytic function. The geometrical and electronic structures of nanoscale catalyst particles play a major role in selectivity, analogous to the behavior of enzymes. Thus, a highly controlled particle-size distribution is desirable. An important goal for the research community is to develop new ways for synthesizing metallic nanoclusters of the desired size, shape, and architecture on nanotemplated surfaces of oxides. Controlled faceting of surfaces can be used as templates for tailoring nanoparticle formation and distribution (below left). Even without such templates, supported nanoparticles exhibit enhanced catalytic activity. A catalyst of gold nanoparticles on titanium dioxide is 10 times more effective at decomposing sulfur dioxide (a primary source of acid rain and smog) than the commercial catalysts used in today's automobile catalytic converters. Nanoparticles of ruthenium on graphite (below right) outperform present commercial catalysts in synthesizing ammonia, one of the largest energy-consuming processes of the industrial world, commanding ~1% of the world's energy production. (Ammonia is fifth on the list of the top 50 U.S. commodity chemicals.)

# Harvesting of Solar Energy with 20% Power Efficiency and 100 Times Lower Cost




Enhanced photovoltaic efficiency in quantum dot solar cells by inverse Auger effect. (courtesy of V. Klimov, Los Alamos National Laboratory; reprinted by permission from Elsevier—see reference 33 on p. 63).




Transmission electron micrographs of cadmium selenide nanocrystals used in a photovoltaic device. Tuning the size and aspect ratio of the nanocrystals gives control over the band gap and electron transport distance. External quantum efficiencies of over 54% have been achieved (courtesy of A. P. Alivisatos, Univ. of California, Berkeley and Lawrence Berkeley National Laboratory).

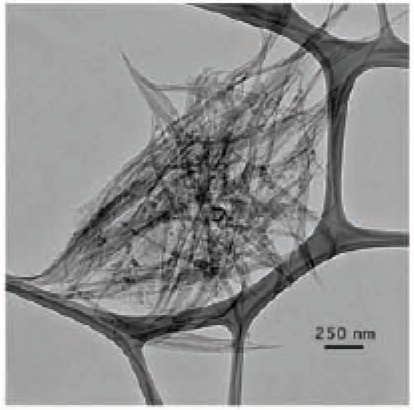
**Nanostructured Photovoltaics: Performance Goals and Opportunities**

At the heart of all photovoltaic cells are two separate material layers, one with a reservoir of electrons that functions as the negative pole of the cell, and the other having vacancies of electrons, called electron holes, that functions as the positive pole. Absorption of light from the sun or another light source by the cell provides energy to drive the electrons from the negative to the positive pole, creating a voltage difference between them, thus enabling the cell to serve as a source of electrical energy. The low efficiency of this conversion of light energy to electrical energy by conventional cells and their cost have prevented photovoltaic cells from being competitive with electrical energy generated from fossil fuels and nuclear power. For nanostructured photovoltaic devices to have a significant impact on energy supply, the cell and module efficiencies must have a lower cost/watt than the projected cost of conventional crystalline silicon photovoltaics. Nanotechnology has considerable potential to produce photovoltaic cells with significant cost reduction, but must do so at cell efficiencies greater than 14-15% and at costs < $100/m$^2$ in order meet a cost goal of $1/W. Since module and balance-of-system costs are major components of the overall expense of photovoltaic systems, cells with efficiencies below 10-12%—even if very inexpensive—will not realize these performance goals. Nanostructured photovoltaic devices must also be able to endure 15-30 years of outdoor operation with daily cycling to temperatures of 80–100ºC at peak rates of solar radiation. Nanostructured devices such as quantum dots allow light to be collected from a broad range of wavelengths (colors) of the sun's spectrum. These devices also gather more than one electron-hole pair per photon because they contain heterostructured absorber layers for broad spectral absorption (see diagram below). This structuring also enhances the efficiency of low-quality materials to accumulate charge carriers or excitons. All have potential for breakthroughs in cost and performance in photovoltaics. Photovoltaics with efficiencies at the level of this grand challenge will clearly make them economically competitive.

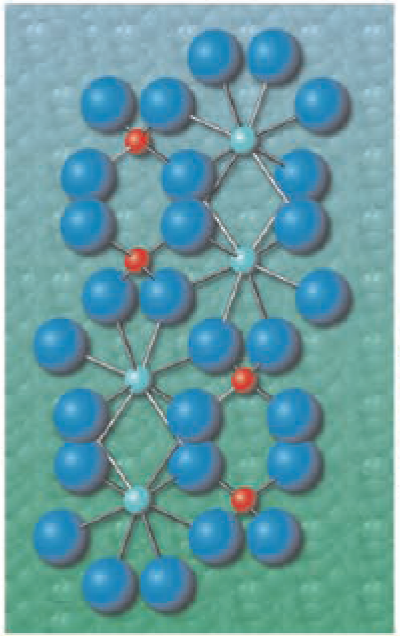
# Reversible Hydrogen Storage Materials Operating at Ambient Temperatures

(a) Electron microscope image of Ti doped $NaAlH_4$ hydrogen storage material (courtesy of R. Stumpf, Sandia National Labs). (b) Crystal structure of the $NaAlH_4$ hydrogen storage material. Al atoms are red, Na atoms are light blue and H atoms are blue (http://www.sc.doe.gov/bes/reports/abstracts.html#NHE). (c) Carbon nanotube storage material with nanoscale Ti clusters for enhanced performance (courtesy of M. J. Heben, A. C. Dillon, K. E. H. Gilbert, P. A. Parilla, T. Gennett, J. L. Alleman, G. L. Hornyak, and K. M. Jones, National Renewable Energy Laboratory). (d) Calculation of $H_2$ storage on a boron doped carbon nanotube (courtesy of Y. H. Kim, Y. Zhao, M. J. Heben, and S. B. Zhang, National Renewable Energy Laboratory).

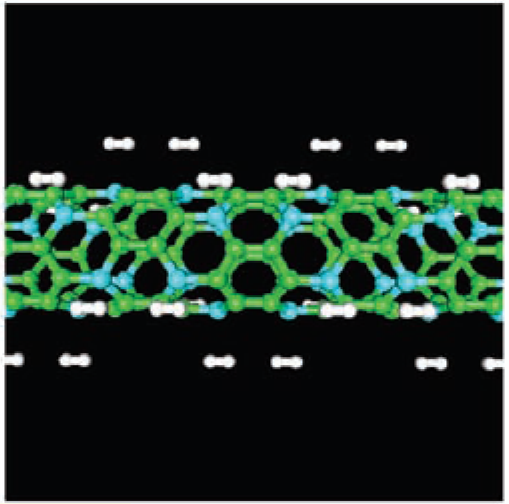
(c)



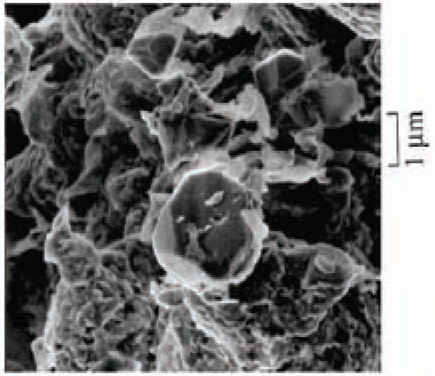

(b)



(d)



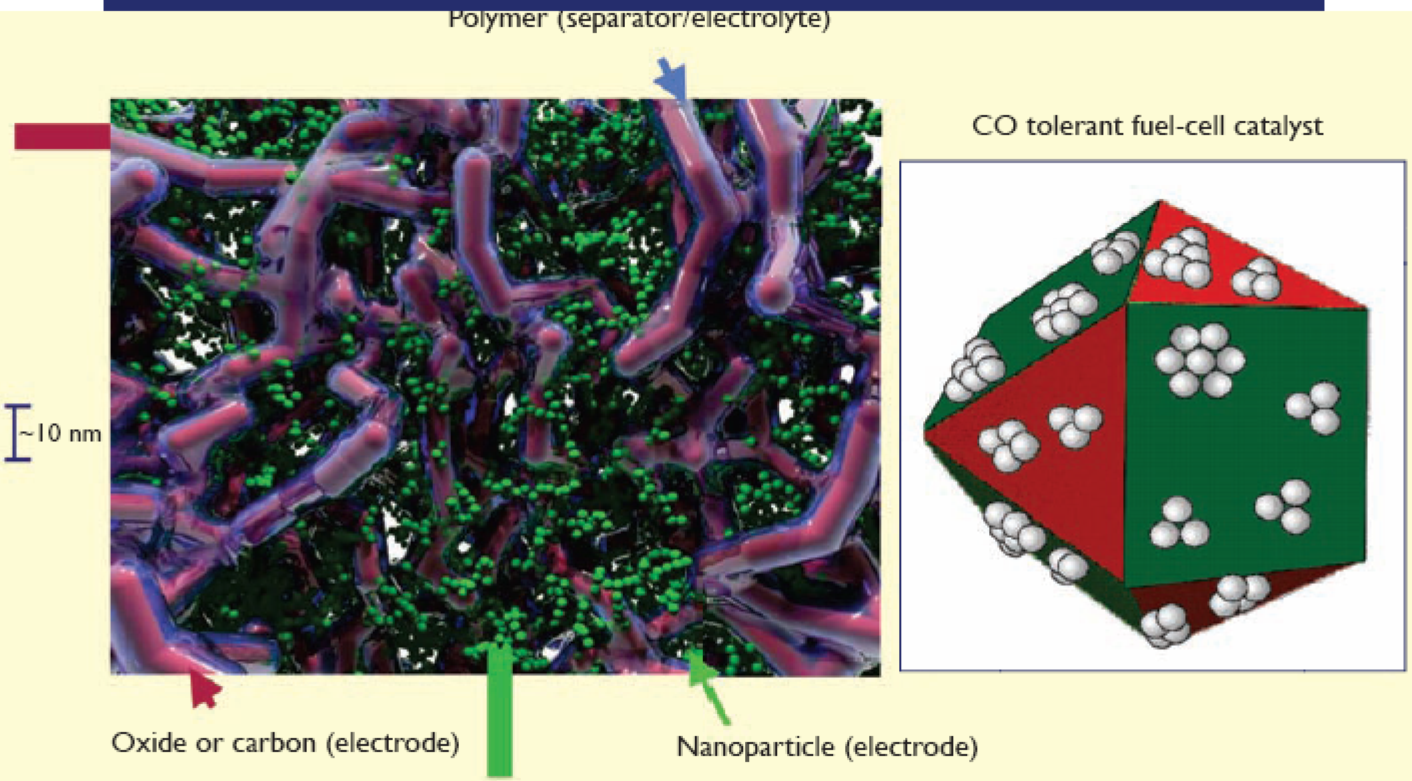
(a)




**Nanomaterials for Hydrogen Storage**

Global energy consumption is expected to increase dramatically in the next decades, driven by rising standards of living and a growing population worldwide. The need for more energy will require enormous growth in energy generation capacity, more secure and diversified energy sources, and a successful strategy to tame greenhouse gas emissions. Among the various alternative energy strategies is building an energy infrastructure that uses hydrogen as the primary energy carrier, connecting a host of energy sources to diverse end uses. A major challenge to realizing a hydrogen economy lays in the development of efficient and safe storage materials for hydrogen. Materials being explored for hydrogen storage require high pressures for forcing the uptake and high temperatures for the release of hydrogen. Nanostructured materials promise to improve both properties. The best material would achieve an optimum compromise between having the hydrogen too weakly bonded to the storage material, resulting in a low storage capacity, and too strongly bonded to the storage material, requiring high temperatures to release the hydrogen. Two candidate materials are complex metal hydrides, which have an intermediate bonding of the hydrogen, and nanostructured carbon-based materials, such as carbon nanotubes. Nanoscale titanium (Ti) additive structures are crucial in both of these systems; to enhance the kinetics of hydrogen uptake and release in the complex metal hydride sodium alanate ($NaAlH_4$), and to increase the storage capacity of carbon nanotubes. Understanding and controlling this nanoscale behavior is critical to the development of hydrogen storage materials for the hydrogen economy.

# Low-Cost Fuel Cells, Batteries, Thermoelectrics, and Ultra-Capacitors Built from Nanostructured Materials




(Figures courtesy of M. S. Doescher, D. R. Rolison, J.W. Long, Naval Research Laboratory and R. Adzic, Brookhaven National Laboratory.)

**Nanoparticles and Nanoarchitectures for Energy Conversion and Storage**

Nanostructured materials offer a number of exciting opportunities for the development of enhanced power storage and conversion. Fuel cell catalysts fabricated with nanoparticles of ruthenium-platinum (Ru-Pt) outperform traditional catalysts in several important ways. They are much more resistant to carbon monoxide poisoning, operating 50 times longer than traditional fuel cell catalysts. Furthermore, the architecture of the nanocatalyst exposes all of the active platinum atoms on the ruthenium nanoparticles (below right), eliminating the need for much of the high-cost platinum, thus driving down the cost considerably and surpassing all DOE targets for low platinum loading.

Nanostructured architectures that employ a highly three-dimensional structuring for power storage (batteries, fuel cells, ultracapacitors, photovoltaics) provide many advantages over existing technologies to minimize power losses, improve charge/discharge rates, and enhance energy densities. Electrodes in these architectures will consist of interconnected ~10 nm domains and mesopores (10–50 nm). An ultrathin, conformal, and pinhole-free separator/electrolyte is electrodeposited onto the electrode nanoarchitecture. Low melting-point metals (mp < 200°C) or colloids fill the remaining mesoporous volume (below left). Controlling the morphology of the electrodes greatly improves charging and discharging rates and increases energy storage and power densities. New lithium batteries with nanostructure electrodes demonstrated over 2500 watts per kilogram power density, which is 10 times greater than conventional lithium batteries.

## Improved Nanoparticle Platinum-Based Catalysts

An example of state-of-the-art synthesis in an energy-related area involves synthesis of a nanocatalyst for hydrogen oxidation in fuel cells. Using techniques from electrochemistry, researchers at Brookhaven National Laboratory synthesized ruthenium nanoparticles with a sub-monolayer of platinum atoms on the surface as catalysts for hydrogen oxidation in fuel cells for the hydrogen economy. This is attractive for catalytic applications due to the potentially low platinum loading of this catalyst, because every platinum atom is on the surface, as shown in Fig. 3.2. The synthesis techniques allow for careful control of the nanocatalyst and for production of quantities for fuel cell testing.

The impact of this nanocatalyst in fuel cells is illustrated in the right panel of Fig. 3.2. This shows the current as a function of time when the fuel cell is exposed to a very high concentration of CO. The blue and green curves show the decay of current that results from CO poisoning in commercial catalysts. The red curve shows that the nanocatalyst demonstrates a significantly enhanced tolerance to CO poisoning compared to the commercial catalysts. This enhanced CO poisoning tolerance in combination with the low platinum loading makes this type of hybrid nanocatalyst of great interest.

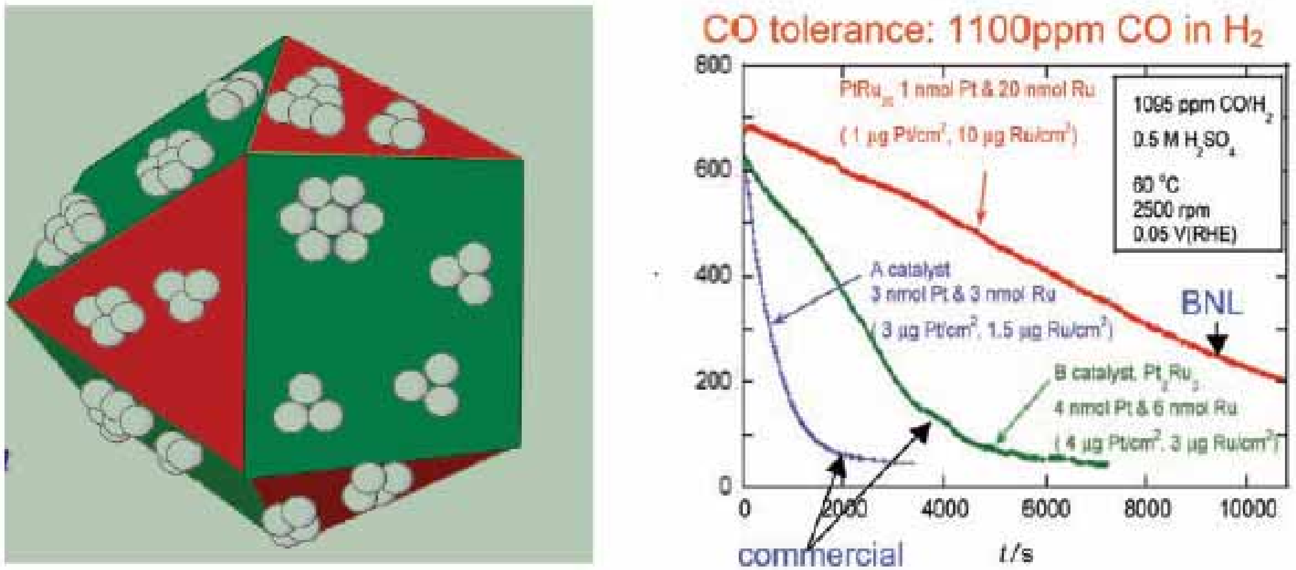
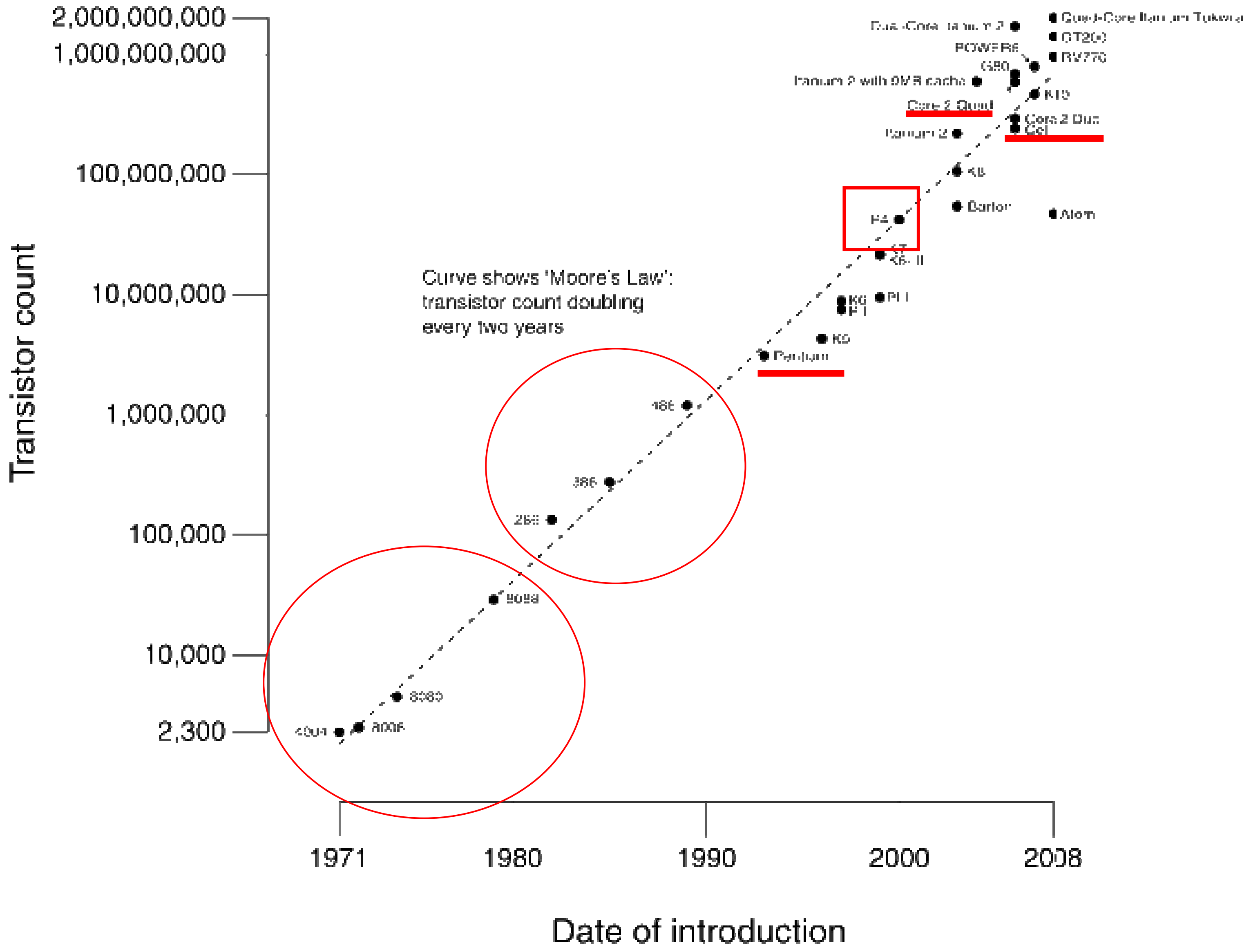



Figure 3.2. Left: Ruthenium nanoparticles with adsorbed platinum atoms, a nanocatalyst for hydrogen reduction. Right: Performance of this nanomaterial (red line) for tolerance to CO poisoning in fuel-cell operation showing greater performance compared to commercial catalysts (green and blue) (courtesy of R. Adzic, Brookhaven National Laboratory [7]).

# CPU Transistor Counts 1971-2008 & Moore's Law



# International Technology Roadmap for Semiconductors*

| First year of volume production | 2001 | 2003*<br>~~2004~~ | 2005*<br>~~2007~~ | 2007*<br>~~2010~~ | 2009*<br>~~2013~~ | 2011*<br>~~2016~~ |
|---|---|---|---|---|---|---|
| Technology Generation<br>(Dense lines, printed in resist) | 130 nm | 90 nm | 65 nm | 45 nm | 32 nm | 22 nm |
| Isolated Lines (in resist)<br>[Physical gate, post-etch] | 90 nm<br>[65 nm] | 53 nm<br>[37 nm] | 35 nm<br>[25 nm] | 25 nm<br>[18 nm] | 18 nm<br>[13 nm] | 13 nm<br>[9 nm] |
| Chip Frequency | 1.7 GHz | 4.0 GHz | 6.8 GHz | 12 GHz | 19 GHz | 29 GHz |
| Transistors per chip (HV)<br>(3 × for HP ; 5 × for ASICs) | 100 M | 190 M | 390 M | 780 M | 1.5 B | 3.1 B |
| DRAM Memory (bits) | 510 M | 1.1 G | 4.3 G | 8.6 G | 34 G | 69 G |
| Gate CD Control<br>($3\sigma$, post-etch) | 5 nm | 3 nm | 2 nm | 1.5 nm | 1.1 nm | 0.7 nm |
| Field Size (mm × mm) | 25 × 32 | 25 × 32 | 22 × 26 | 22 × 26 | 22 × 26 | 22 × 26 |
| Chip Size (mm)<br>(2.2 × for HP ; to 4 × for ASIC) | 140 | 140 | 140 | 140 | 140 | 140 |
| Wafer Size (diameter) | 300 mm | 300 mm | 300 mm | 450 mm | 450 mm | 450 mm |

*Semiconductor Industry Association (SIA), December 2001. *Possible 2-year cycle.

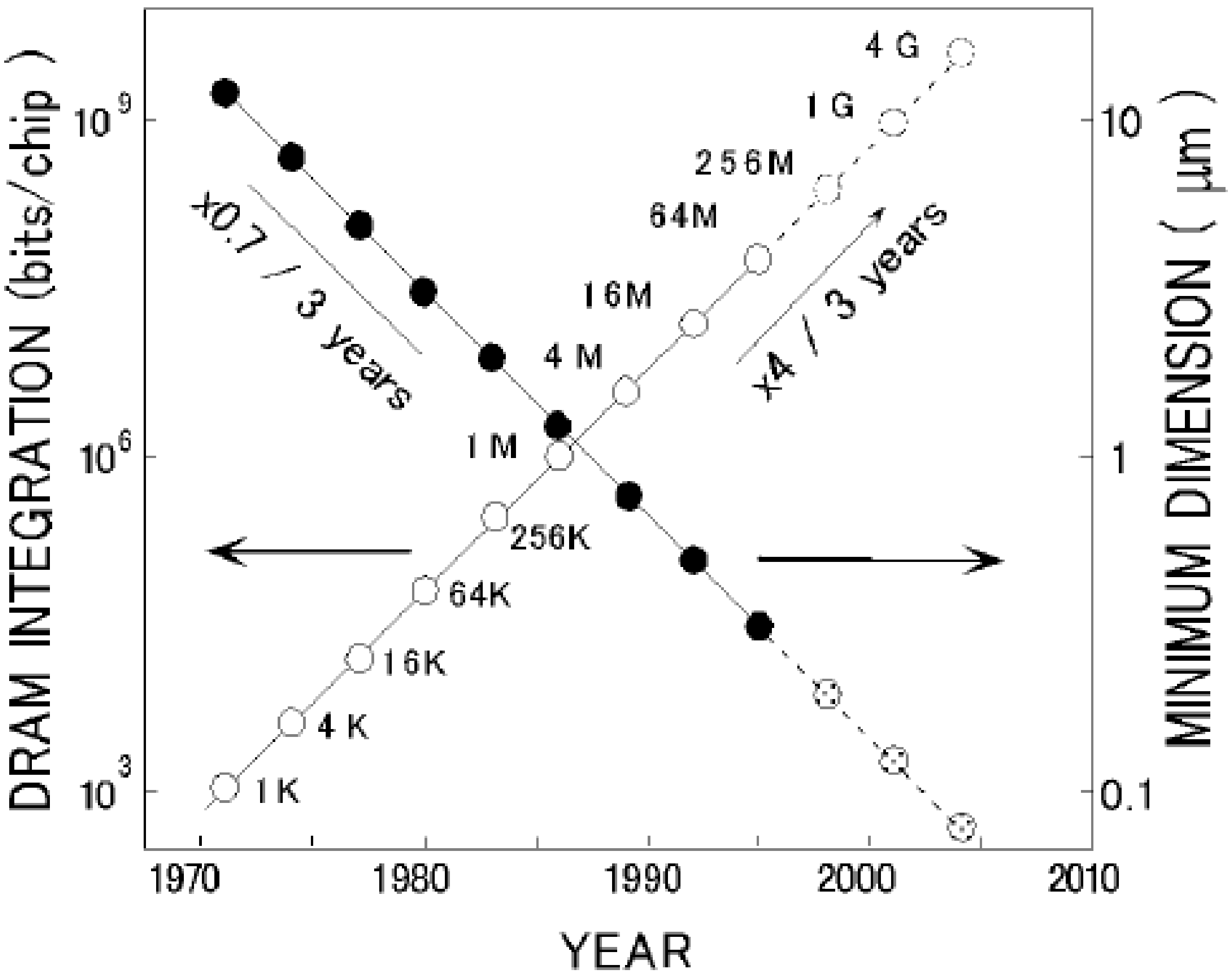



Fig. 2 Trend curve of silicon ULSIs: the minimum dimension has been shrunk by a factor of 0.7 while the integration quadrupled every 3 years for more than 30 years.

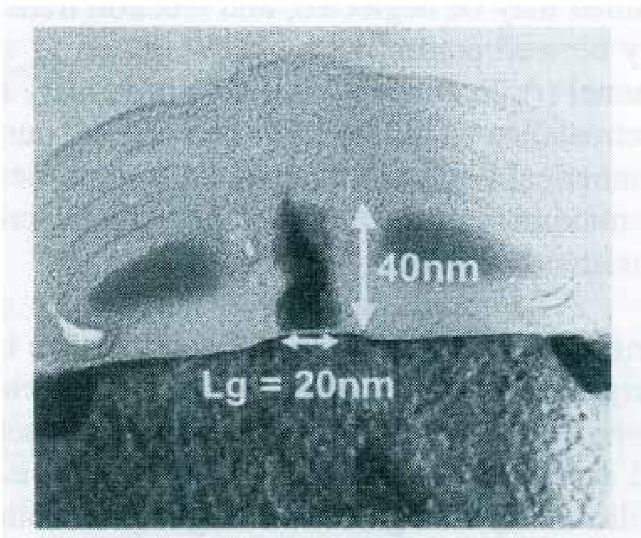



Fig. 3 TEM image of Lg=20nm MOSFET. (R. Chau, Abst. Si-Nanoelectronics Workshop, p. 2, (2001).

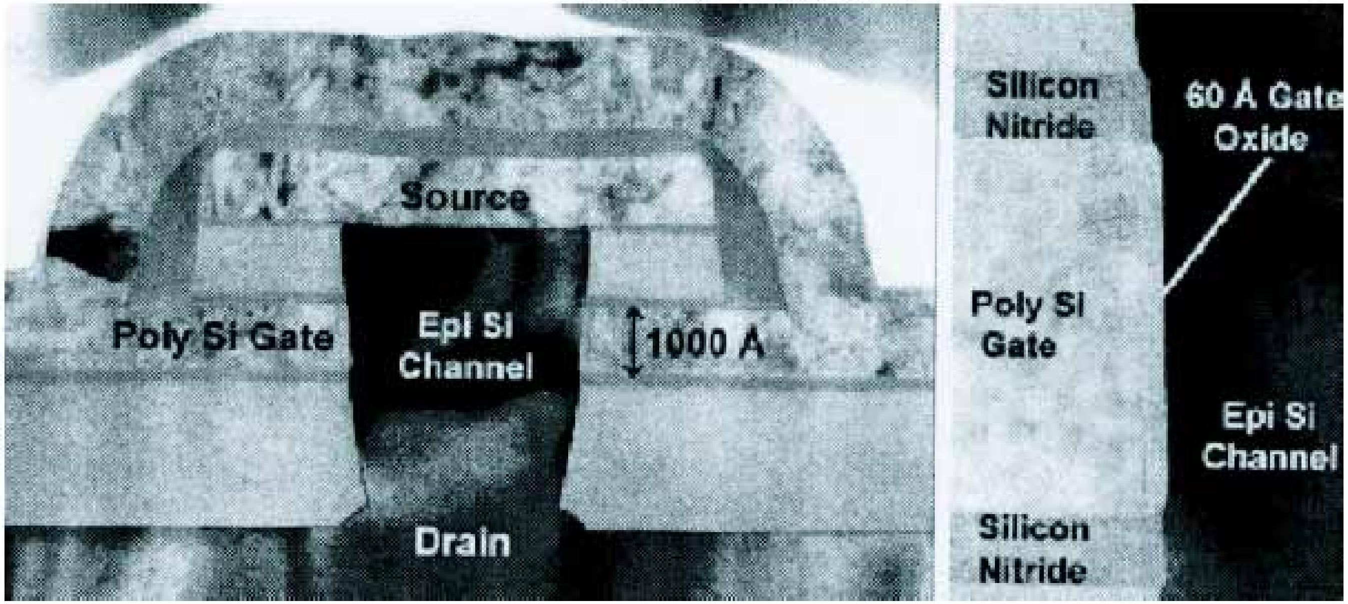



Fig. 4 VRG(Vertical Replacement Gate) MOSFET. (J. M. Hergenrother et al., Tech. Dig. IEDM'99, p. 75, (1999). (© 1999 IEEE).

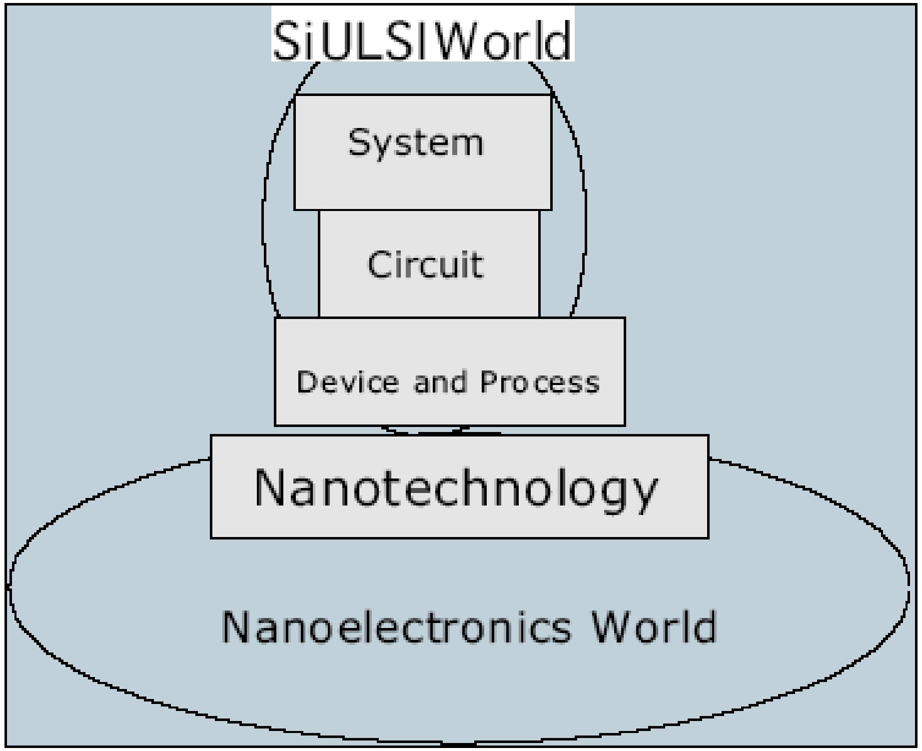



Fig. 5 A technology hierarchy. for ULSIs. The most advanced device size of ULSI world is in a nanotechnology region.

# History

- 1959, R. P. Feynman, “ There’s plenty of room at the bottom”.
- 1985, G. K. Binnig and H. Rohrer, Scanning Tunneling Microscope (STM).
- 1985, Curl, Kroto and Smalley, Buckyballs, fullerene, Carbon 60.
- 1991, Iijima, Carbon nanotubes.
- 1993, Eigler, Quantum confinement of surface electron waves.

# There's Plenty of Room at the Bottom

*by Richard P. Feynman,* December 29th 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech)

"What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can't see exactly what would happen, but I can hardly doubt that when we have some *control* of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do....

When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc....

Now, you might say, ``Who should do this and why should they do it?'' Well, I pointed out a few of the economic applications, but I know that the reason that you would do it might be just for fun. But have some fun!"

- Manipulating and controlling things on a small scale.
- There is plenty of room at the bottom, not just “there is room at the bottom”.
- Information on a small scale.
- Miniaturization by vaporation.
- Rearranging the atoms.
- Quantized energy levels and the interactions of quantized spins.
- At the atomic level, we have new kinds of forces, new kinds of possibilities and new kinds of effects.

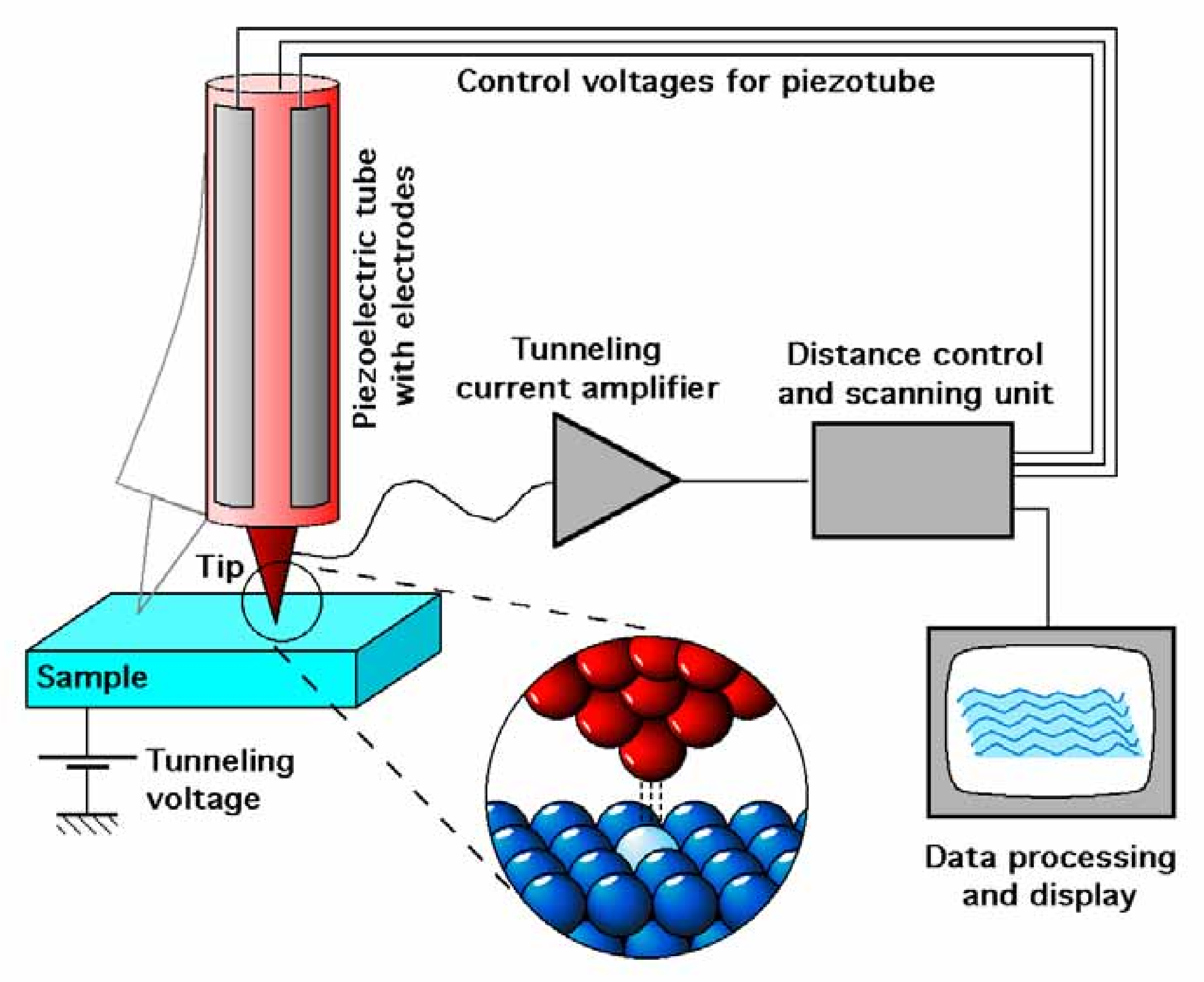
# Feynman prize

- **1) Design and Construct a Functional Nano-scale Robotic Arm (Nano-scale machine).**
- **2) Design and Construct a Functional Nano-scale Computing Device.**

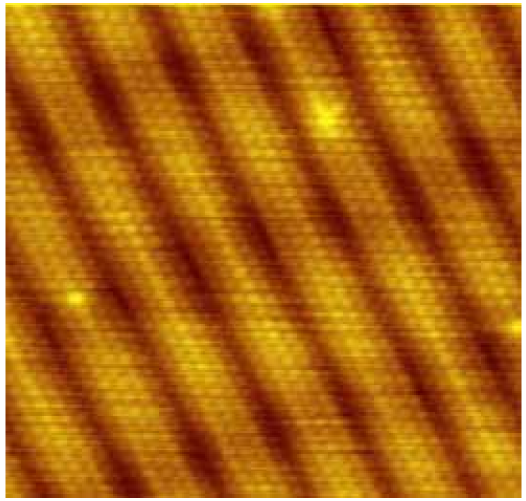
# Scanning Tunneling Microscope


Nobel Laureates Heinrich Rohrer and Gerd Binnig

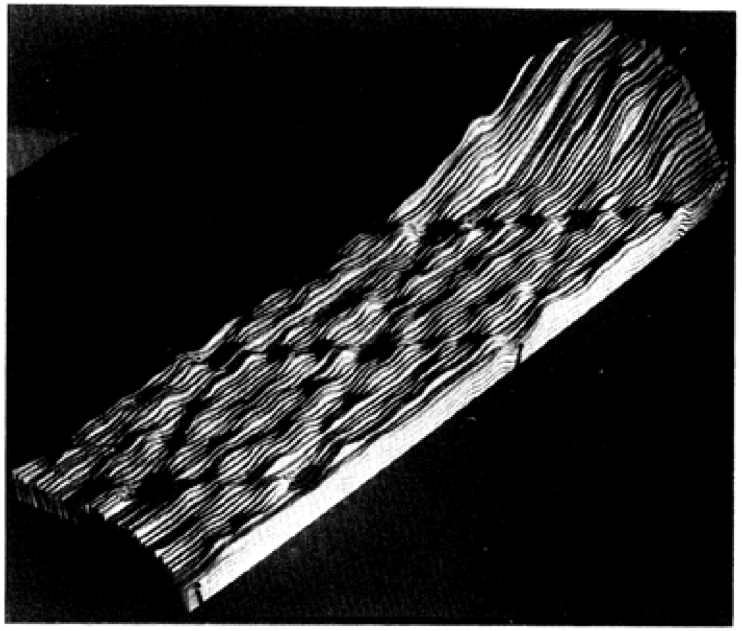
# Scanning tunneling microscope

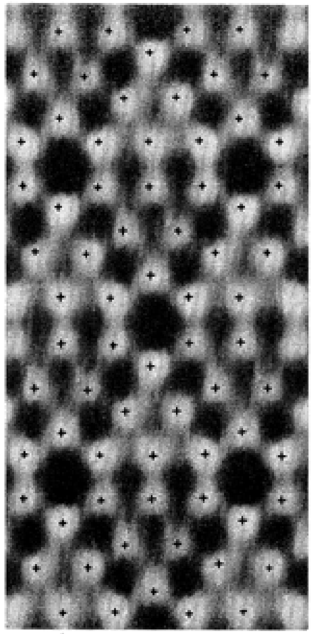


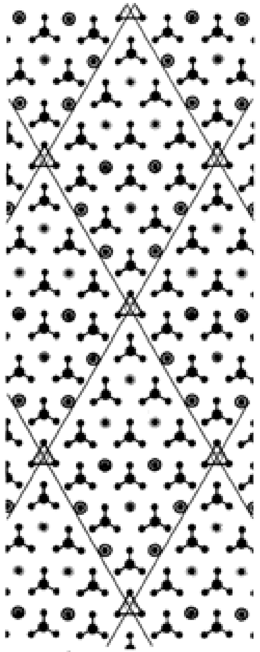

Au surface

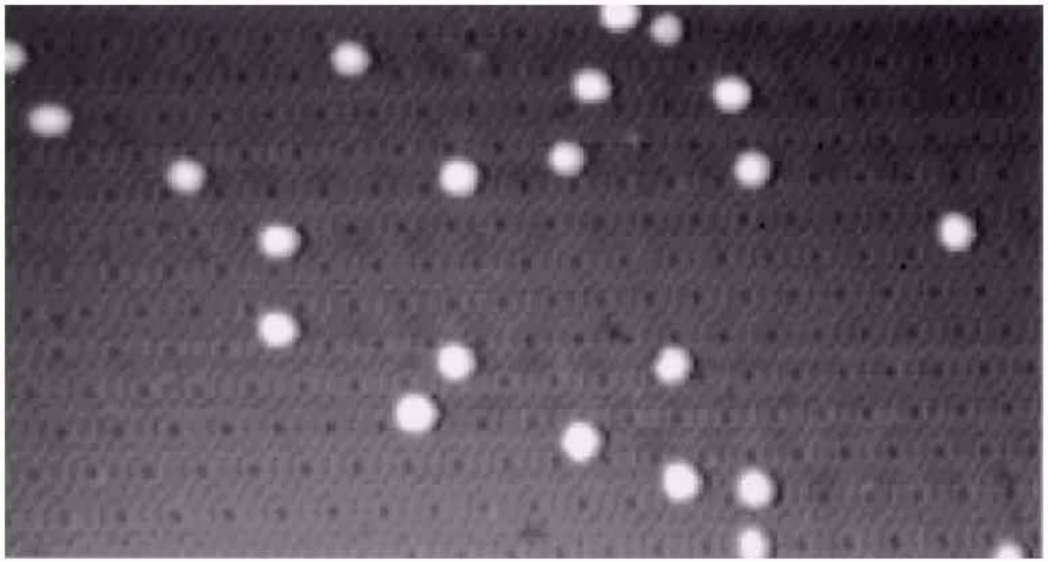


# Si (7x7) surface structure

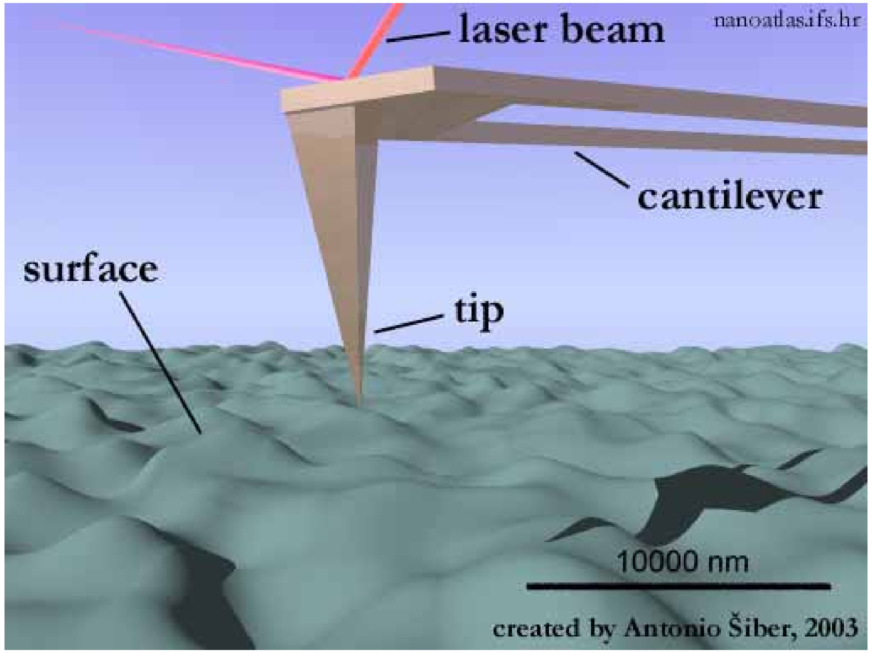


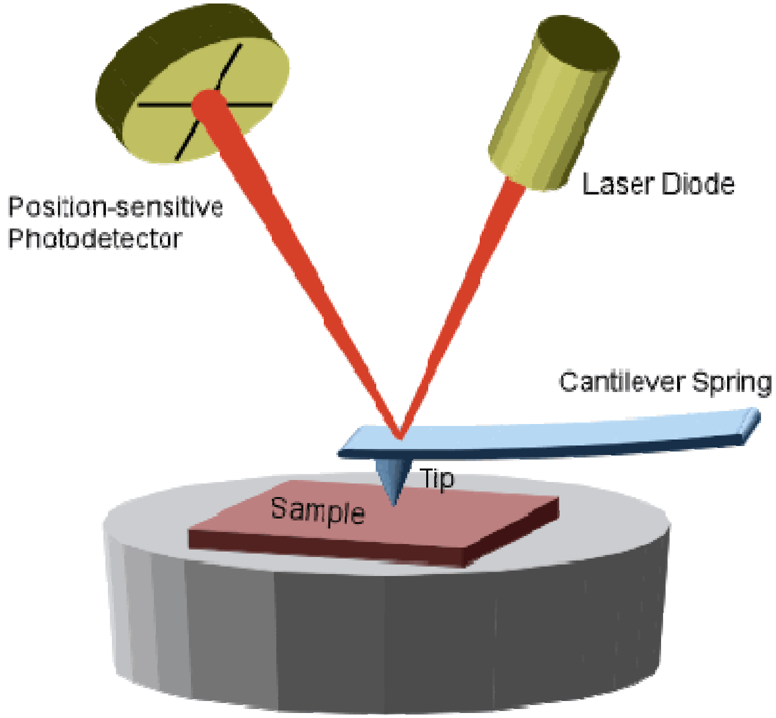


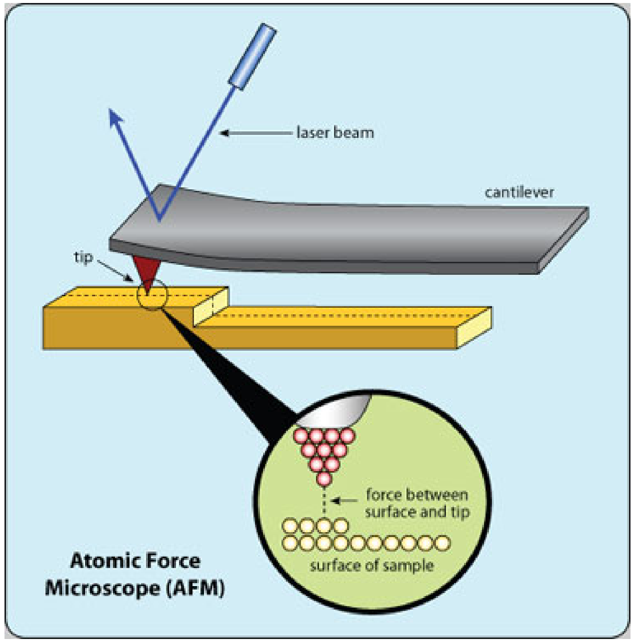




# Atomic Force Microscope



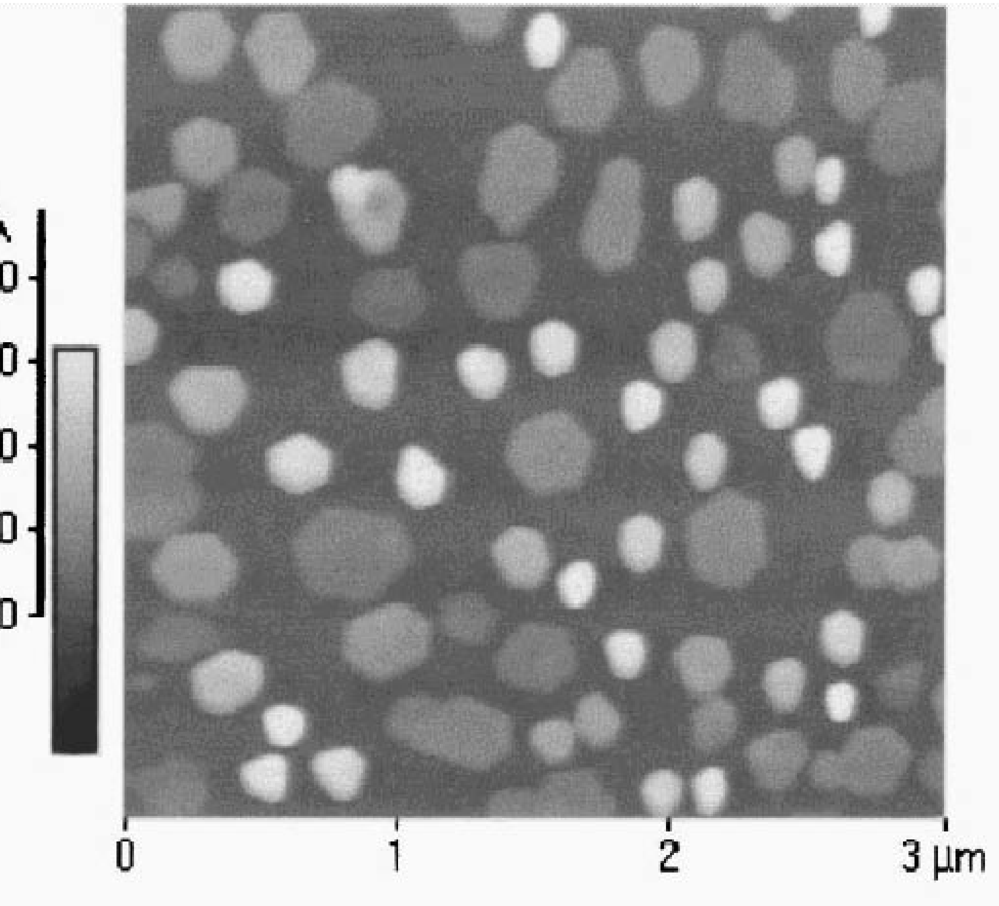



# $C_{60}$

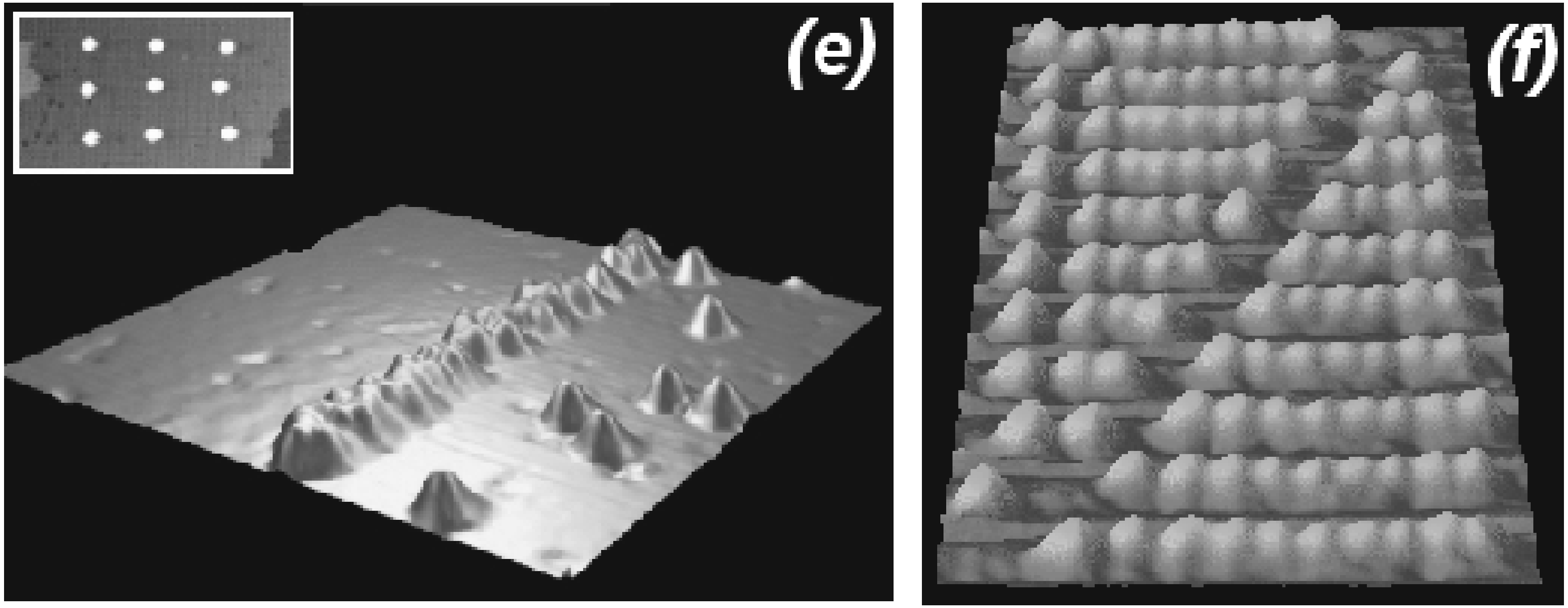
(a)

(b)



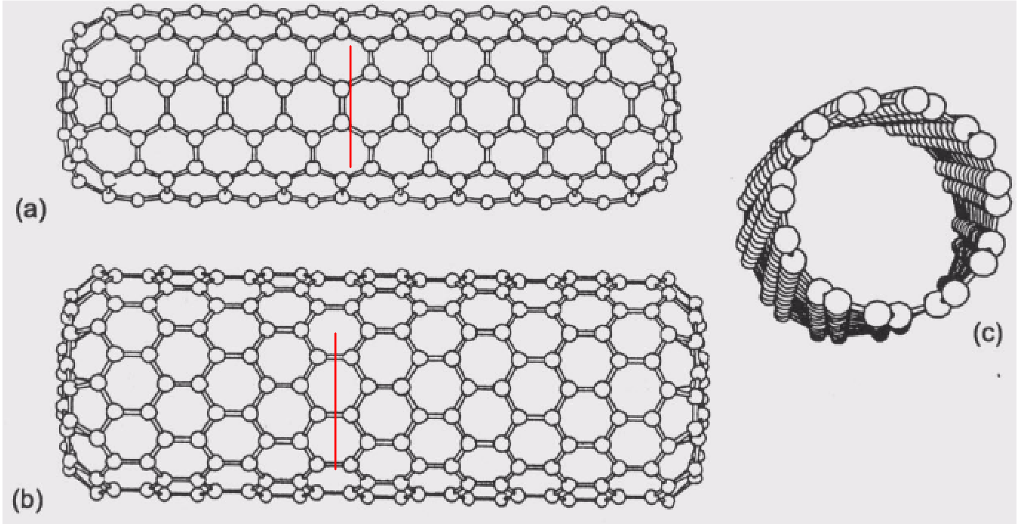

(a) A schematic diagram of the structure of C60. Black lines represent double bonds, lighter lines single bonds. (Adapted from an image available at the Sussex Fullerene Group's Fullerene Gallery website: http://www.sussex.ac.uk/Users/kroto/fullgallery.html).
(b) C60 thin films on Si (111).

# Manipulations of $C_{60}$ molecules




(e) Room temperature molecular manipulation—formation of a wire of C60 molecules (~25 nm long) on Si(100)(2 x 1). The inset is a 2D array of C60 molecules on Si(100) (Moriarty *et al* 1998a, b).
(f ) A molecular abacus formed from C60 molecules aligned along a step on a Cu surface (Cuberes *et al* 1996).

# Carbon Nano-tubes




The three types of nanotube: (a) armchair, (b) zigzag and (c) chiral.

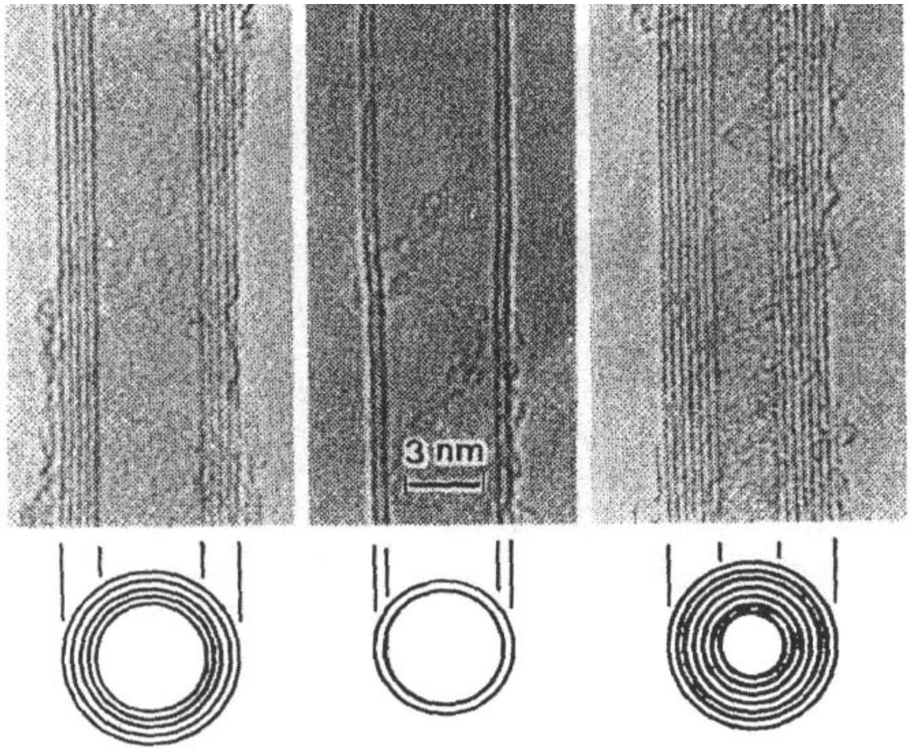
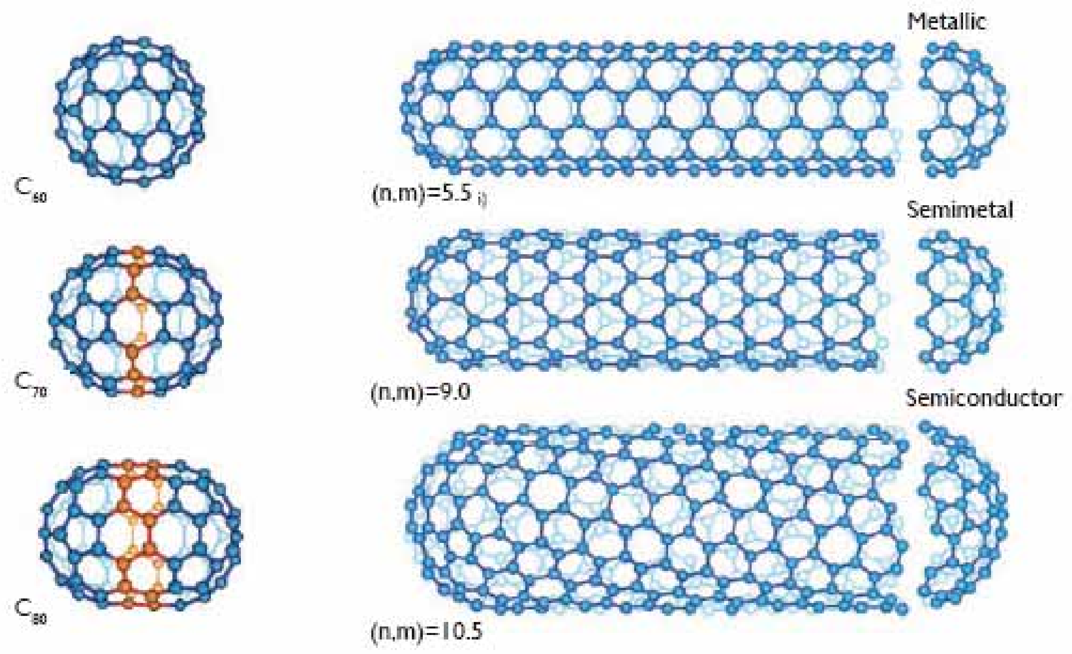
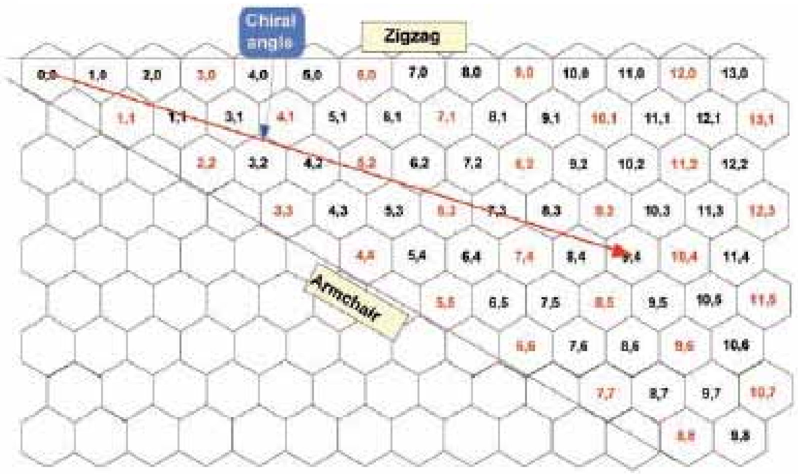


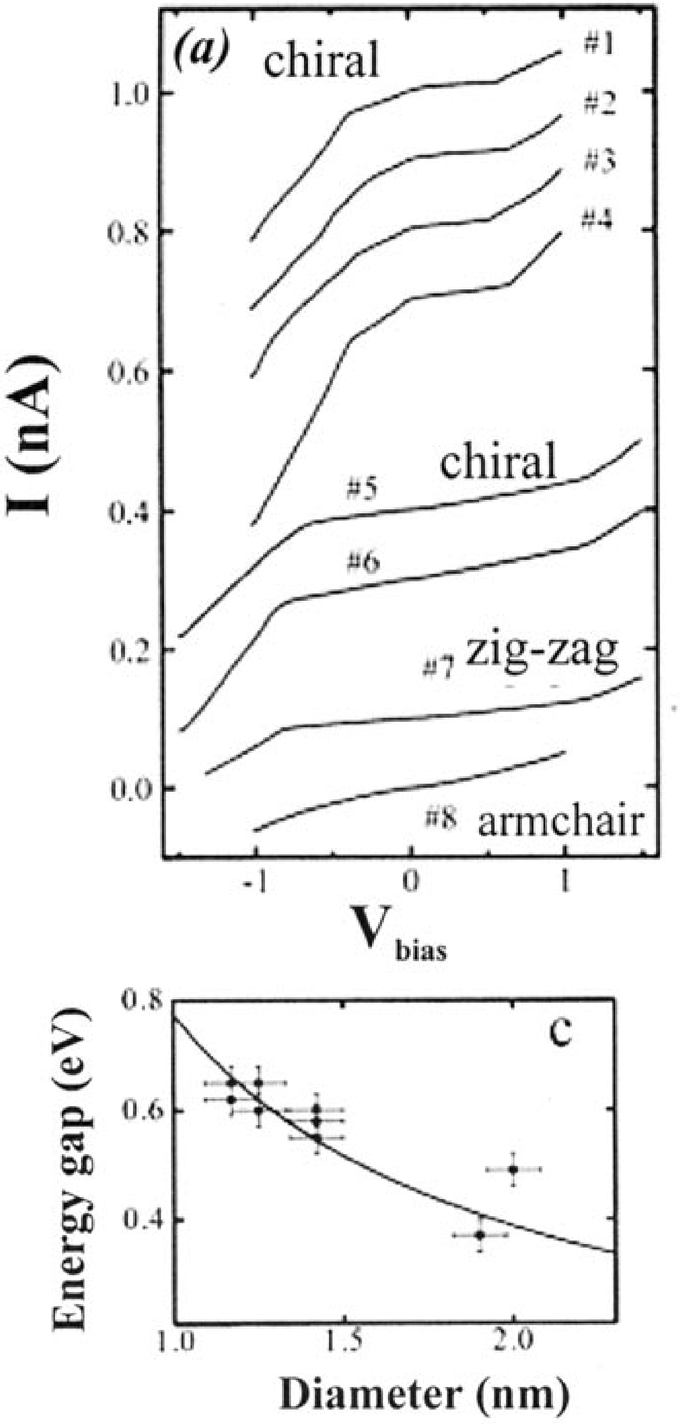

**Figure 46.** TEM images of multi-walled carbon nanotubes (Iijima 1991).

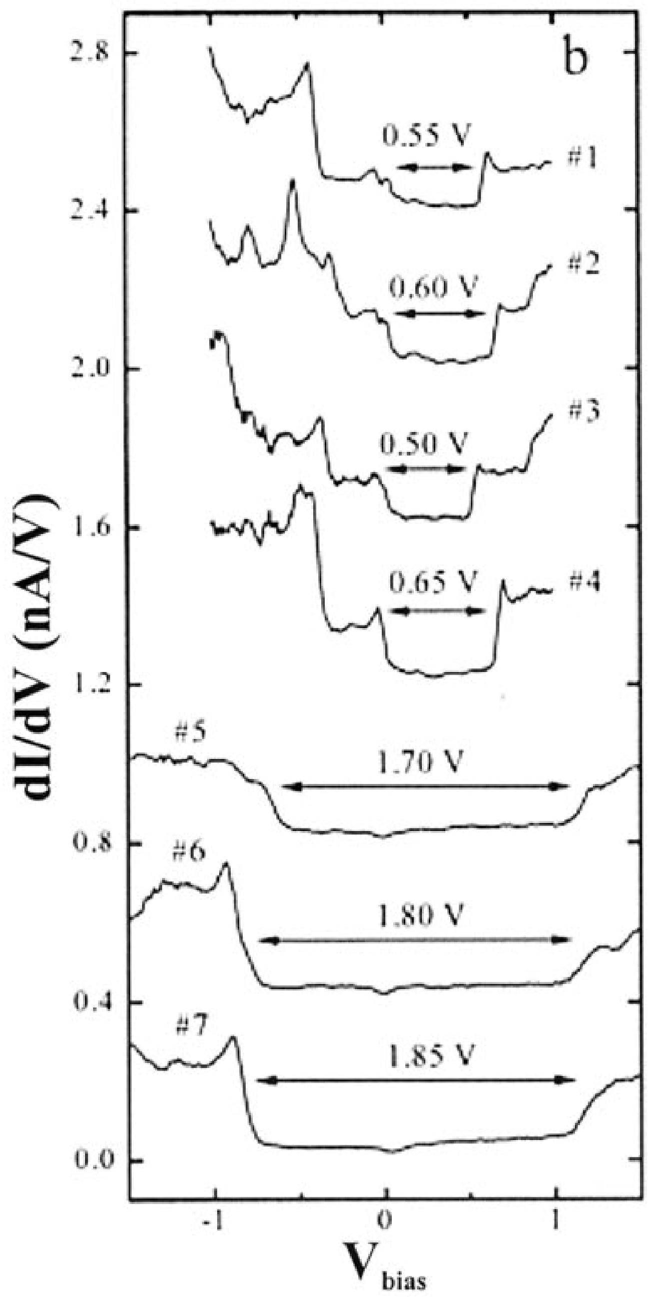
# Carbon Nanotubes

Carbon nanotubes exhibit a wide range of remarkable properties. Mechanically, they are as much as 100 times stronger in tension than steel. One of the most remarkable properties of carbon nanotubes is how they conduct electricity. Three types of nanotubes are possible, called *armchair*, *zigzag*, and *chiral* nanotubes, depending on how the two-dimensional graphene sheet is "rolled up." Whether they are are conducting or semiconducting is governed by the chirality of the carbon nanotube as indexed by the coordinates n,m. Carbon nanotubes will be metallic when n=m, semi-metal for n-m evenly divisible by 3, and a direct bandgap semiconductor otherwise (courtesy of R. Smalley, Rice University).



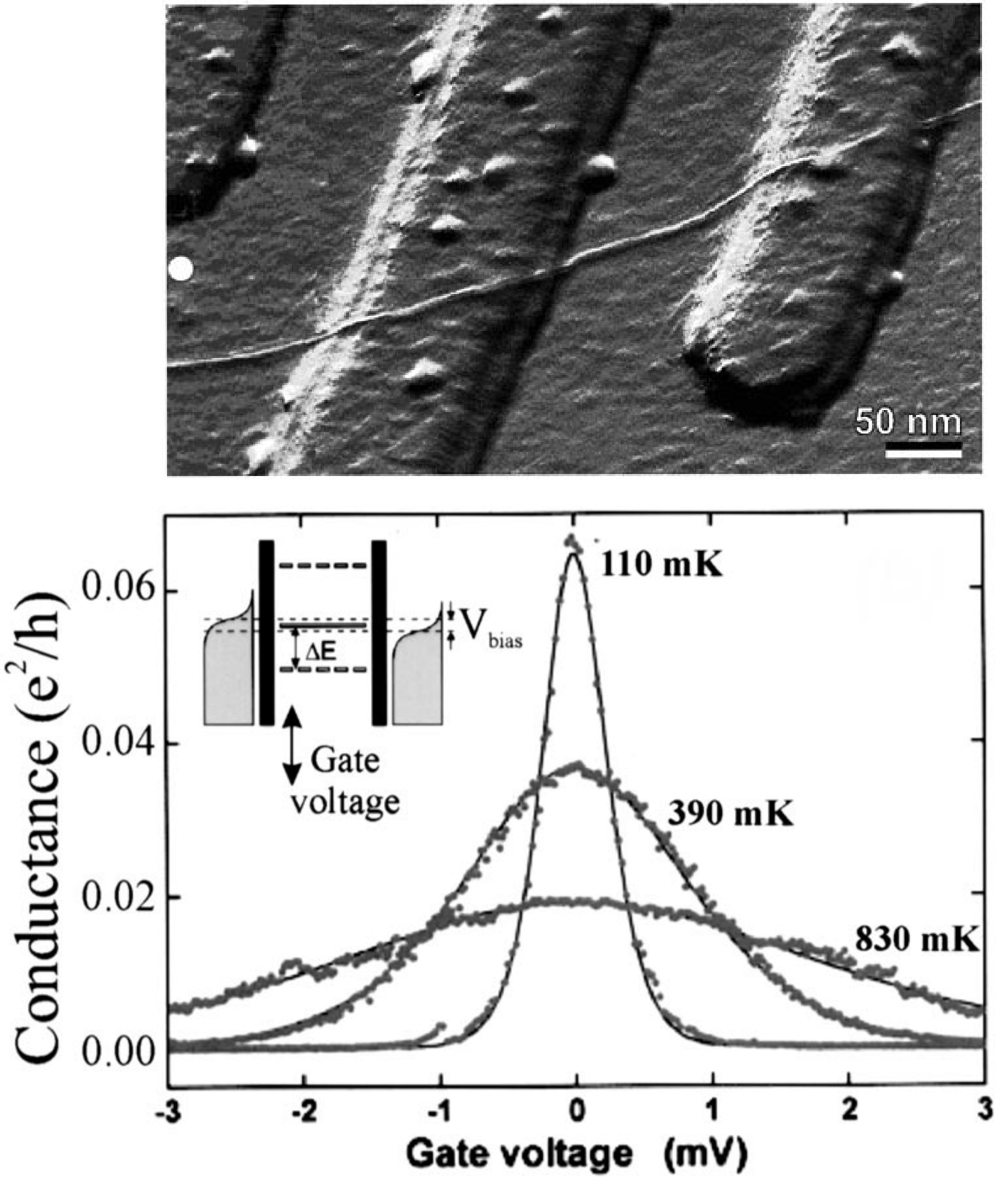





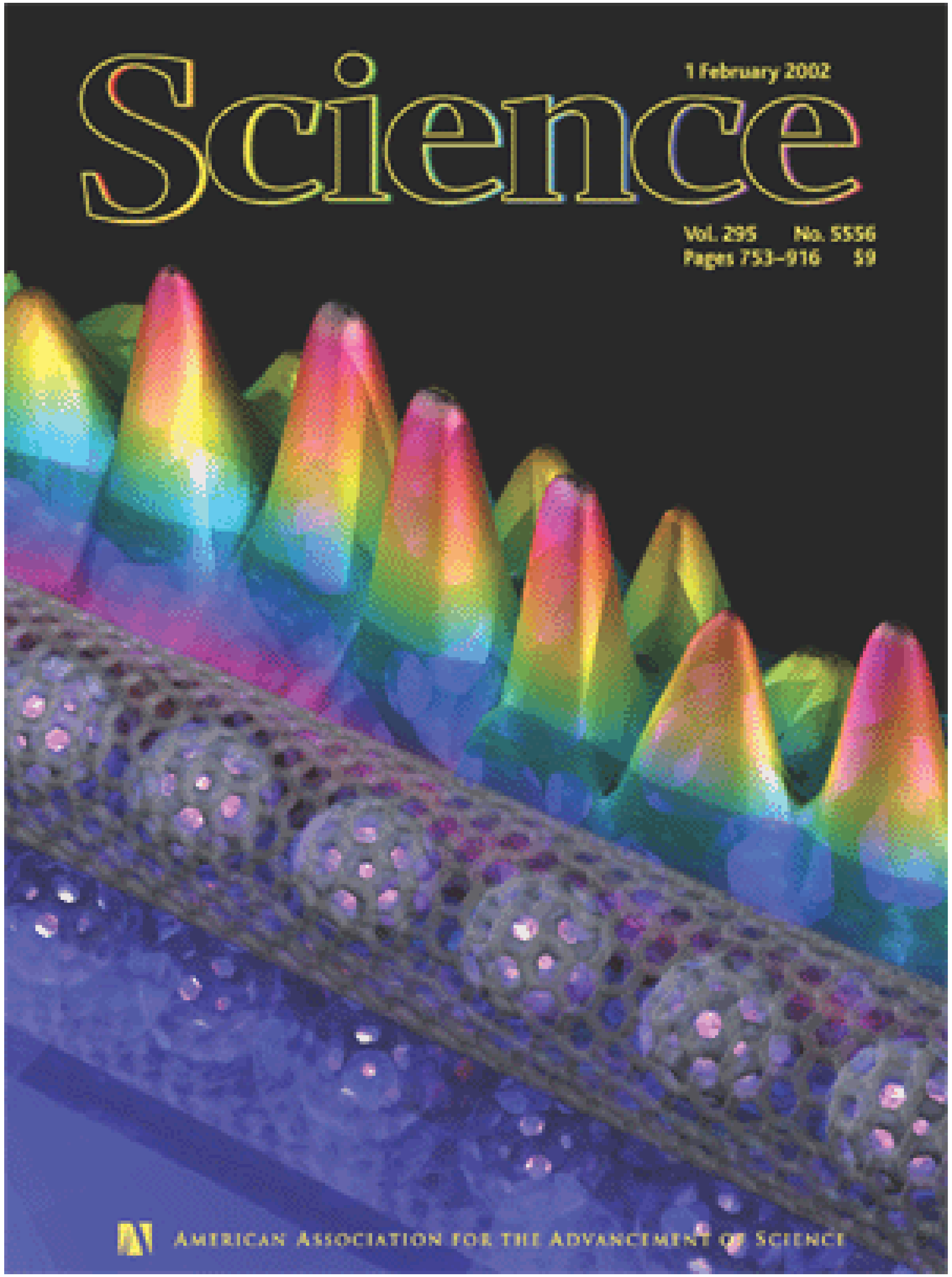






The tube density of states



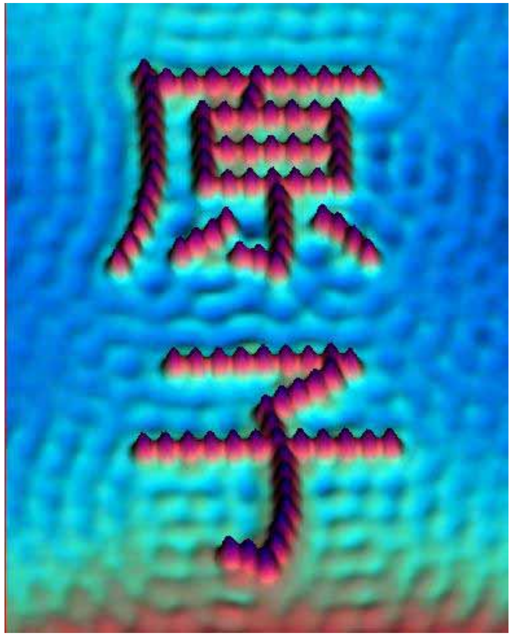

(a) An AFM tapping mode image of a carbon nanotube on top of a Si/SiO2 substrate with two 15 nm thick Pt electrodes. (b) Conductance versus gate voltage at low bias voltage for the tube shown in (a). The solid lines are fits corresponding to a model of a single molecular level weakly coupled to two electrodes as depicted in the inset (Tans *et al* (1997);




Cover page of Feb. 1, 2002 Science magazine.

$C_{60}$ molecules encapsulated in a single-wall carbon nanotube peapod.

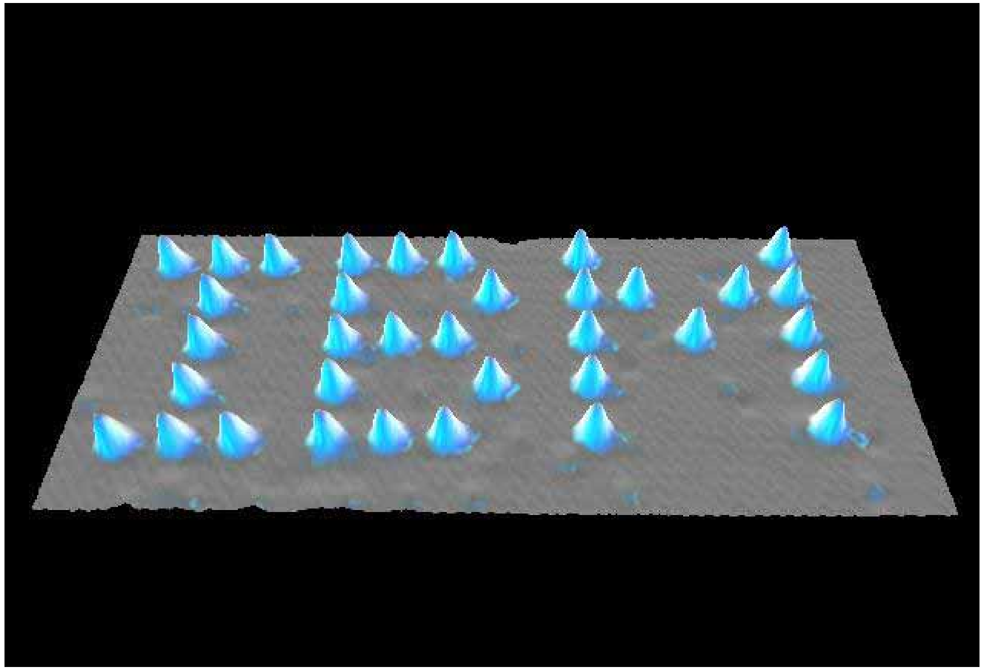
In the background are the electron waves in this one-dimensional nanostructure, mapped with a STM.



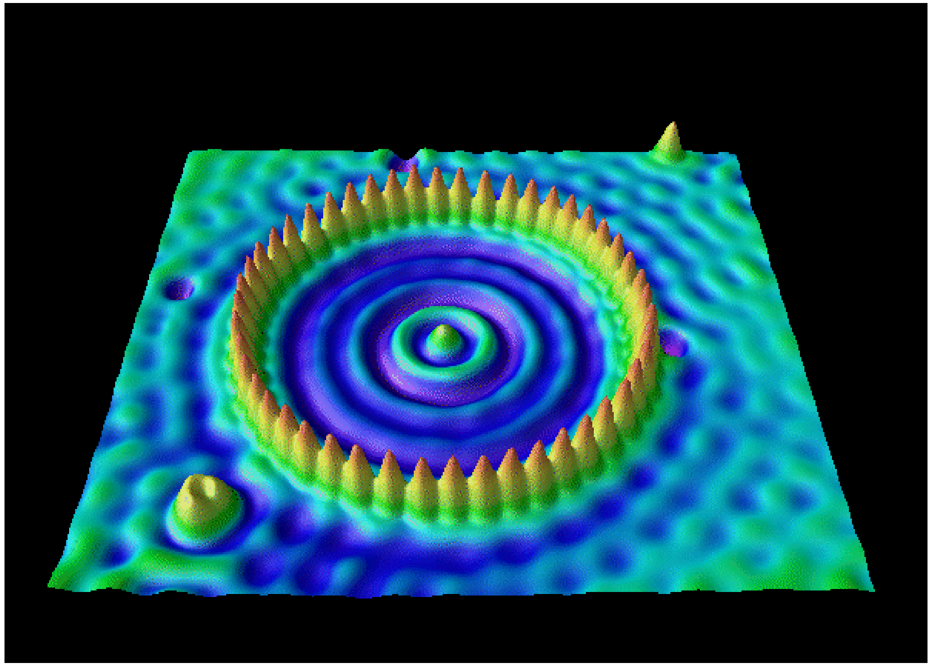

Chinese characters

“Atom”

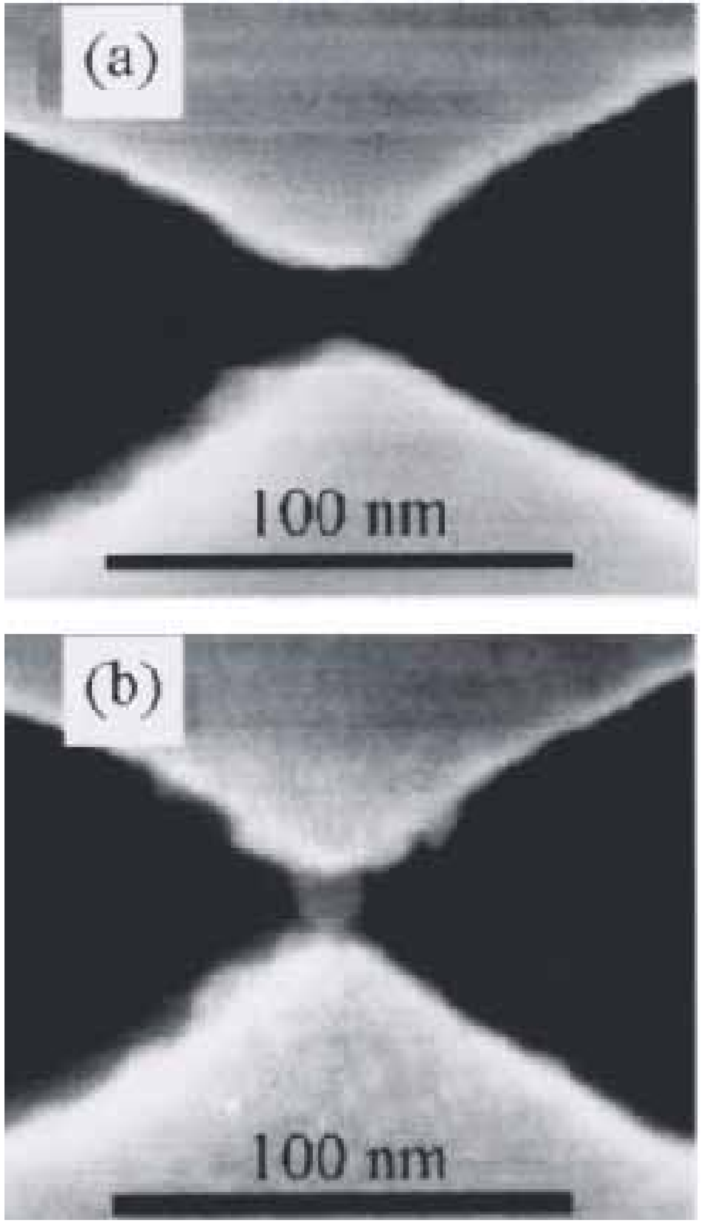
Xe on Ni




Fe on Cu



# Coulomb blockade & single electron transistor



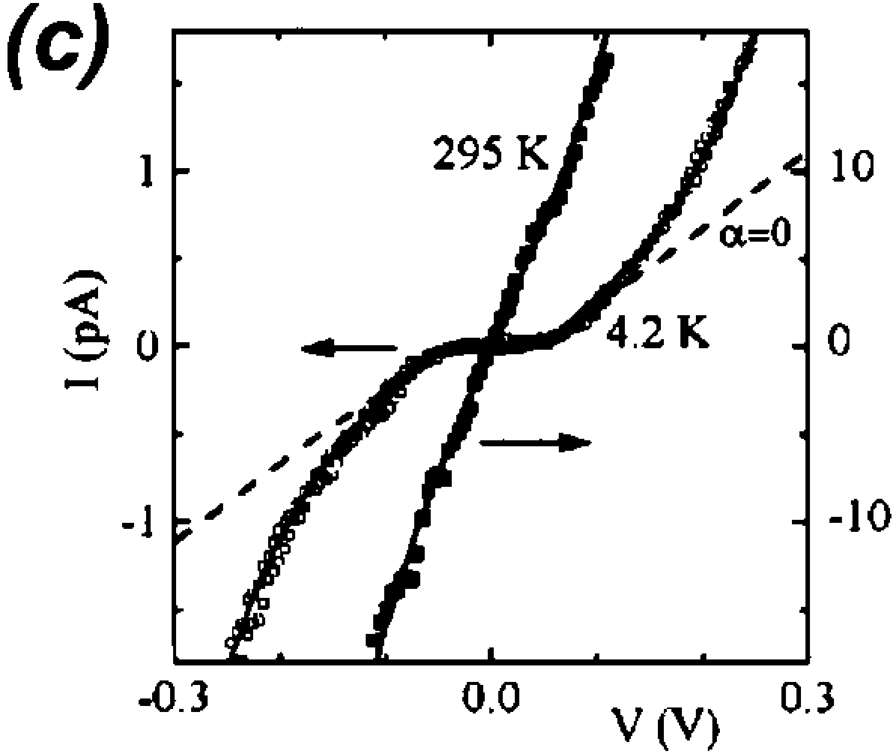
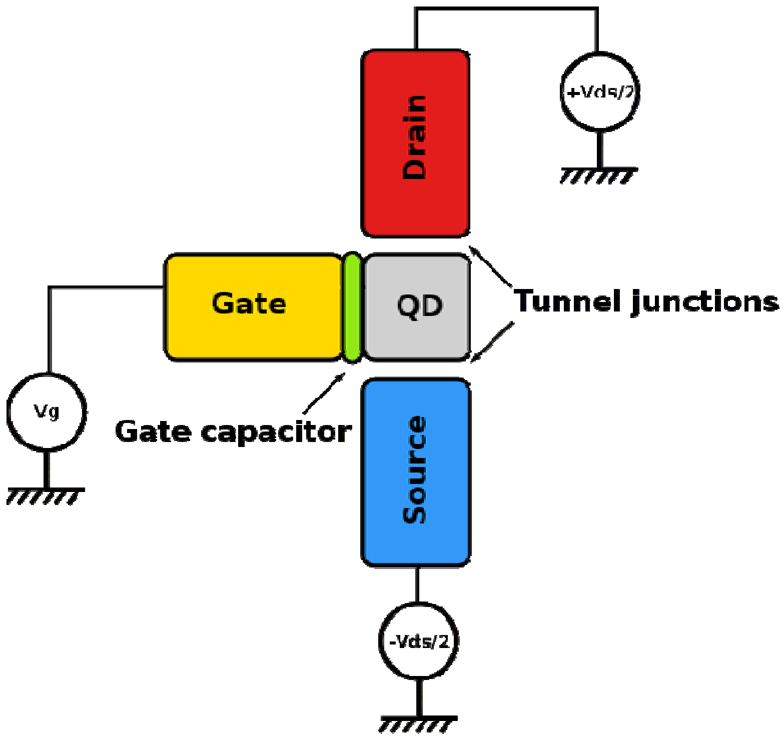
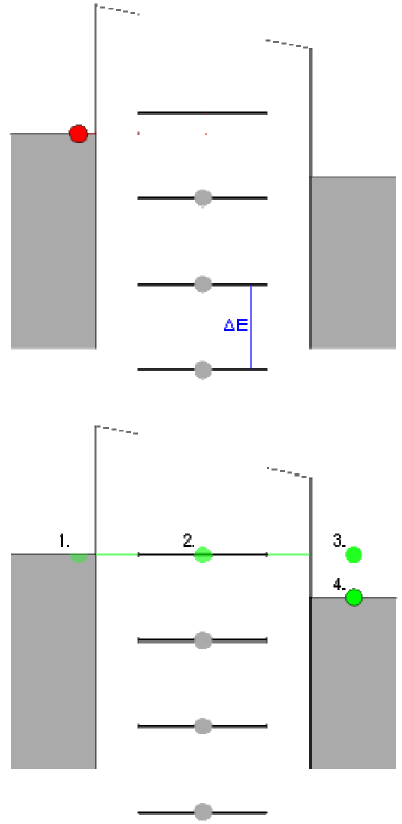
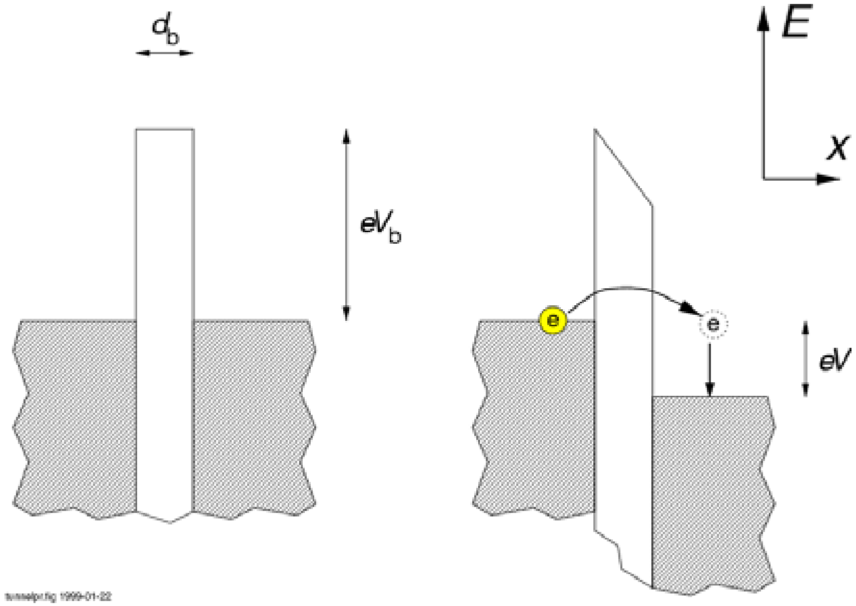
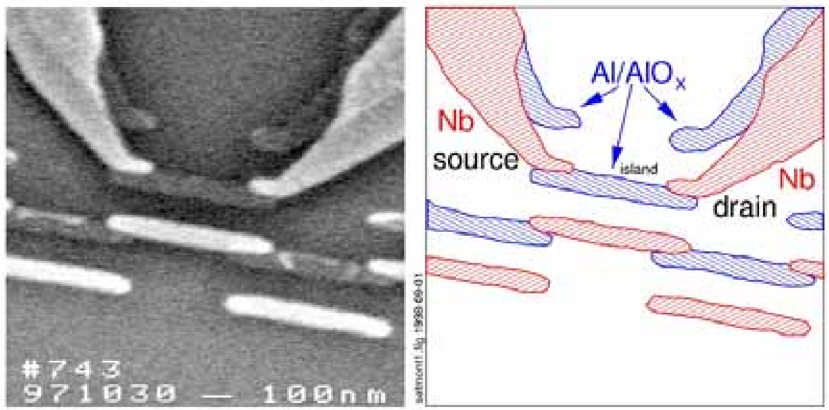




**Figure 23.** (a), (b) Electrostatic trapping of a Pd colloidal nanoparticle between two electrodes.
(c) *I*–*V* characteristics measured at 4.2 K.[46]

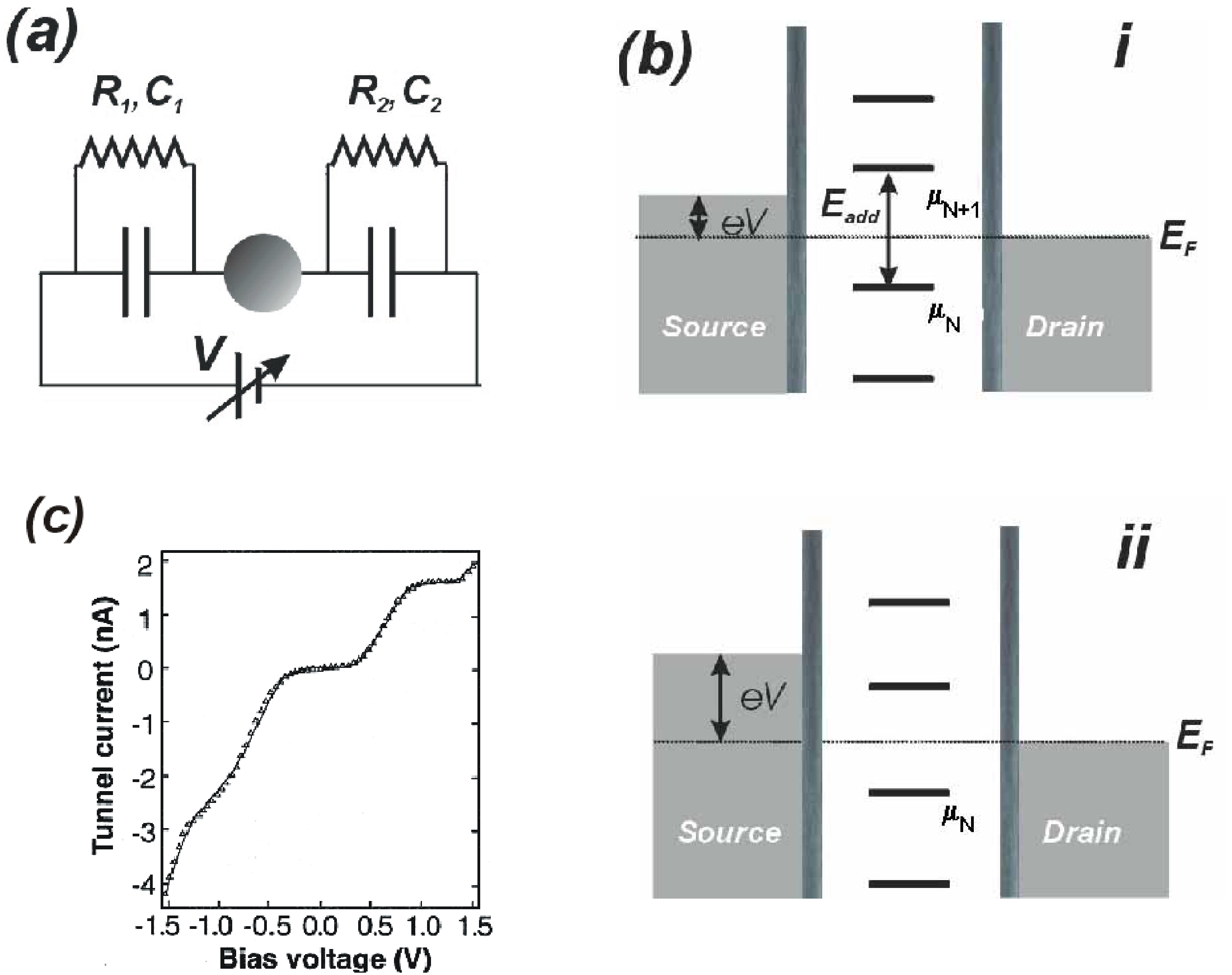

Drain
+Vds/2
Gate
QD
Tunnel junctions
Vg
Gate capacitor
Source
-Vds/2


ΔE
1.
2.
3.
4.


$d_b$
$eV_b$
e
e
eV
E
x


#743
971030 — 100nm
Al/AlO$_x$
Nb
source
island
Nb
drain

# Coulomb staircase



# Importance of nanotechnology

- The quantum mechanical (wavelike) properties of electrons inside matter are influenced by variations on the nanoscale. By nanoscale design of materials it is possible to vary their micro and macroscopic properties, such as charge capacity, magnetization and melting temperature, without changing their chemical composition.

- A key feature of biological entities is the systematic organization of matter on the nanoscale. Developments in nanoscience and nanotechnology would allow us to place man-made nanoscale things inside living cells.  It would also make it possible to make new materials using the self-assembly features of nature.
- Nanoscale components have very high surface to volume ratio, making them ideal for use in composite materials, reacting systems, drug delivery, and chemical energy storage.

- Macroscopic systems made up of nanostructures can have higher density than those made up of microstructures. They can also be better conductors of electricity. This can result in new electronic device concepts, smaller and faster circuits, more sophisticated functions, and greatly reduced power consumption simultaneously by controlling nanostructure interactions and complexity.

# Questions

- Analytical tools?
- Fabrication methods?
- Applications?

# Important fields

- Nanoelectronics: Quantum dots, nanowires, single electron transistor.
- Nanoelectromechanical system (NEMS): From microelectromechanical system (MEMS) to nanoscales.
- Nanomaterials: Carbon nanotubes, nanostructures, quantum confinement, nanophotonics, spintronics, nanoprobes (STM, AFM, TEM).
- Nanobiology, nanomedicine.

# Important topics of Nanotechnology

- Fundamental theory.
- Properties of nanostructures.
- Fabrications of nanostructures.
- Measurements of nanostructures.
- New nanodevices and nanosystems.

# Recommend references


- F. J. Owens & C. P. Poole Jr., “The physics and chemistry of nanosolids”, Wiley, 2008.
- C. Kittel, “Introduction to Solid State Physics”, 8th edtion, Wiley, 2005.

# Wed sites

- The international Small Technology Network (http://www.nanotechnology.com).
- Nanotechwire (http://www.nanotechwire.com).
- U.S. National Nanotechnology Initiative (http://www.nano.gov).
- Institute of nanotechnology (http://www.nano.org.uk).
- Nanotechweb (http://nanotechweb.org).
- Nanovip (http://www.nanovip.com).
- A to z of Nanotechnology (http://www.azonano.com).
- Foresight Institute (http://www.foresight.org/).

# Nanotechnology journals

- Nano Letters.
- Journal of nanotechnology.
- Nature nanotechnology.
- Journal of nanoscience and nanotechnology.
- Journal of nanoparticle research.

# Notes

- Nanotechnology involves the creation and manipulation of materials at the nanometer (nm) scale either scaling up from single groups of atoms or by refining or reducing bulk materials.
- Nanotechnology is not a single technology or scientific discipline.
- Nanotechnology is a multidisciplinary grouping of physical, chemical, biological, engineering, and electronic, processes, materials, applications and concepts in which the defining characteristic is one of size.