Frontiers in Nanoscale Science

- Introduction to nanoscience
- The art of making nanostructures
- Quantum structures and devices
- Carbon nanotechnology
Max Planck Society for the Advancement of Science

• Independent, non-profit organization (an incorporated association), founded in 1948.

• Successor to the Kaiser Wilhelm Society, which itself was founded in 1911.

~1‘810 Mio. € Total budget of the MPS:
  80% by the German Federal Government and the individual states,
  20% own income & project funding.

~13‘200 Staff members,
  including ~ 5‘200 scientists

~7‘000 Student assistants, graduates, post docs, guest scientists, etc.
Max Planck Campus, Stuttgart

Intelligent Systems

Solid State Research

Solid State Research Precision Laboratory
The Max Planck – EPFL Center serves as a forum for cooperative research by bringing together scientists of the Max Planck Society (MPS) and the École Polytechnique Fédérale de Lausanne (EPFL). In joint projects scientists of the Center explore novel scientific aspects of (bio)molecular nanostructures at the interface between physics, chemistry, engineering and life sciences. The Center also creates new educational opportunities for students and young scientists.

http://mpg-epfl.mpg.de
MPS-EPFL Center MNST

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- Dr. H. Klauk

MPI Intelligent Systems
- Prof. J. Spatz
- Dr. P. Fischer
- Dr. C. Pacholski
- Dr. C. Boehm
Visiting Max-Planck
November 3 & 4, 2016
Nanotechnology ?
Nanorobots

Die Zeit, June 6 (2002)
Quantum Size Effect

CdSe Nanocrystals

2 nm → 7 nm

wavelength [nm]

energy [eV]

nanocrystal radius [nm]

ΔE

E_{gap}
Westminster Abbey, East-Window

Medieval Nanotechnology

Lycurgus Cup
Michael Faraday discovered in 1851 that the colors of ruby gold were due to its finely divided state.
According to experts, the colloidal gold is absorbed through the skin and helps stimulate incorporation blood circulation, increasing enzyme activity, restoring and reconstructing the damaged cells. Also induces the addition of mineral nutrients, while preventing skin sagging. In addition, gold nanoparticles eliminate biological contaminants generated by the body and encapsulated in clogged pores. This is one of several causes of tired, prematurely aged and dull skin.
„Blue Man“
Paul Karason
Richard Feynman (1959)
„There´s plenty of room at the bottom“
Molecular Machines

ATP Synthase
„Enlightenment“

Optical Microscope

Robert Hooke (1635-1703)
Antoni van Leeuwenhoek (1632-1723)
Richard Feynman (1959)

“What good would it be to see individual atoms distinctly? 
…. look at the atoms and see where they are.”
Titan Transmission-Electron-Microscope
Atomic Resolution

Strontium titanate

Aluminium nitrid
Gerhard Richter, "Graphit", 2005
Wondermaterial Graphene
Wondermaterial Graphene

- thinnest imaginable material (few Å)
- largest surface area (~2700 m²/g)
- strongest material (theoretical limit)
- stiffest known material (stiffer than diamond)
- most stretchable crystal (up to 20% elastically)
- record thermal conductivity (outperforming diamond)
- highest current density at RT (10⁶ times of copper)
- completely impermeable (even He atoms cannot squeeze through)
- highest intrinsic carrier mobility (100x larger than Si)
- lightest charge carriers (zero rest mass)
- largest mean free path (micron range)
• $sp^2$-hybridized carbon
• mother of graphitic materials

2-D graphene
- warping
- rolling
- stacking

0-D fullerene
1-D carbon nanotube
3-D graphite
2D Dirac Materials
Images of Atoms

Erwin Müller ➔ Field Ion Microscopy (1951)

first atomic images (1955)
„Sensing“ Atoms

Scanning Tunneling Microscope (1981)

Heini Rohrer

Gerd Binnig
Gold Surface
Cu Atoms at Work

14 K
x 230
fast motion

30 nm x 32 nm
Brownian Motion

15 K

x 230

fast motion

60 nm x 60 nm
Brownian Motion ⇒ Einsteins most cited (1905) publication

Über die von der molekular-kinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen."

Ann. Phys. 17, 549 (1905)
Artificial Earthquake

- 5 t synchronized Football Team
- Maximum Amplitude: 0,004 mm
Artificial Earthquake

- One jump suffices
- Maximum Amplitude: 0.0005 mm
  = 500,000 Picometer !!!
Precision Laboratory at MPI Stuttgart

ultimate noise-free environment
Precision Laboratory at MPI Stuttgart
Perfect Isolation in the Cube

vibrational level:  < 10 nm/s

acoustic shielding:  60 dB

electromagnetic shielding:  60 – 100 dB
Quantum Measurements in the Cube
10 mK – 14 T – UHV STM

UHV compatible dilution fridge

Energy Resolution $\Delta E = 11.4 \pm 0.3 \mu$eV

Energy Resolution in a Tunnel Junction

- environmental impedance
- capacitive noise
STM at the Quantum Limit

\[ \Delta E_{P(E)} = \gamma (2E_C k_B T)^{1/2} \]

Spectroscopy of Single Molecules

Elastic vs. Inelastic Tunneling

\[ I \sim e^{-\kappa z} \int_0^{eV} dE \cdot LDOS_{Sample}(E_F + E) \]

\[ \frac{dI}{dV} \mid_{Vr} \sim LDOS_{Sample}(E_F + eV) \]
Vibrations of Single Molecules

Acetylen

\[
\begin{align*}
\text{Cu(100)} & \quad \text{C}_2\text{H}_2 \\
& \quad \text{C}_2\text{D}_2 \\
& \quad \text{C}_2\text{HD}
\end{align*}
\]
STM Point Contacts

Co/Cu(111)

Conductance [$G_0 = \hbar/e^2$]

Tip height [Å]
Beyond Imaging
Rearranging the Atoms

“But I am not afraid to consider the final question as to whether, ultimately – in the great future – we can arrange the atoms the way we want; the very atoms, all the way down!”
Information on a Small Scale

Fe_{12}

magnetic bit
Single Atom Magnetic Memory
Nanotechnology: Big Business?
Nanotechnology: Applications
Lotus Effect
Computer Miniaturisation !!!!!!!!
“... I do know that computing machines are very large; they fill rooms. Why can’t we make them very small ...”

R. Feynman (1959)
The first Transistor
Bardeen, Brattain & Schockley
(1949)

The first Integrated Circuit
Noyce & Kilby
(1958)
Gordon E. Moore, Co-founder, Intel Corporation.

Electronics, Volume 38, Number 8, April 19, 1965

“The incredible shrinking Transistor

“With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip.”
Small, Micro, Nano ...... Molecular

14 nm 2\textsuperscript{nd} Generation Tri-gate Transistor

Ultimate Scale : Molecular Dimensions

TEM image of SiO\textsubscript{2} Barrier
Carbon Electronics
Carbon Nanotube Computer

142 transistor computer – Turing complete
Energy !!!!!
Sustainable Energy Supply
Antoine de Lavoisier

Dans la nature rien ne se crée, rien ne se perd, tout change
Blackbody Radiation

The diagram illustrates the spectral irradiance (kW/m²/nm) of different blackbody temperatures (in K). The curves represent the radiation output at various wavelengths (nm), with temperatures ranging from 3000 K to 7000 K. The rainbow spectrum indicates the distribution of colors corresponding to different wavelengths.
LED
Single Molecule LED

Single Molecule Photonics

light harvesting

light emission
Energy Conversion

Artificial Photosystem II

Natural Photosystem II

Solar Energy

2 H₂O → O₂ + 2 “H₂”

2 “H₂” + 2 CO₂ → [CH₂O] Fuel
Water $\text{H}_2\text{O}$

Energy Density
4450 Wh/l
Photocatalytic Water Splitting

\[ \text{H}_2\text{O} + 2\text{e}^- + 2\text{h}^+ \rightarrow \text{O}_2 + \text{H}_2 \]


Energy Density

4450 Wh/l
Harvesting Osmotic Energy with MoS$_2$ Nanopores

J. Feng et al., Nature (2016) doi:10.1038/nature18593
Insight must precede application