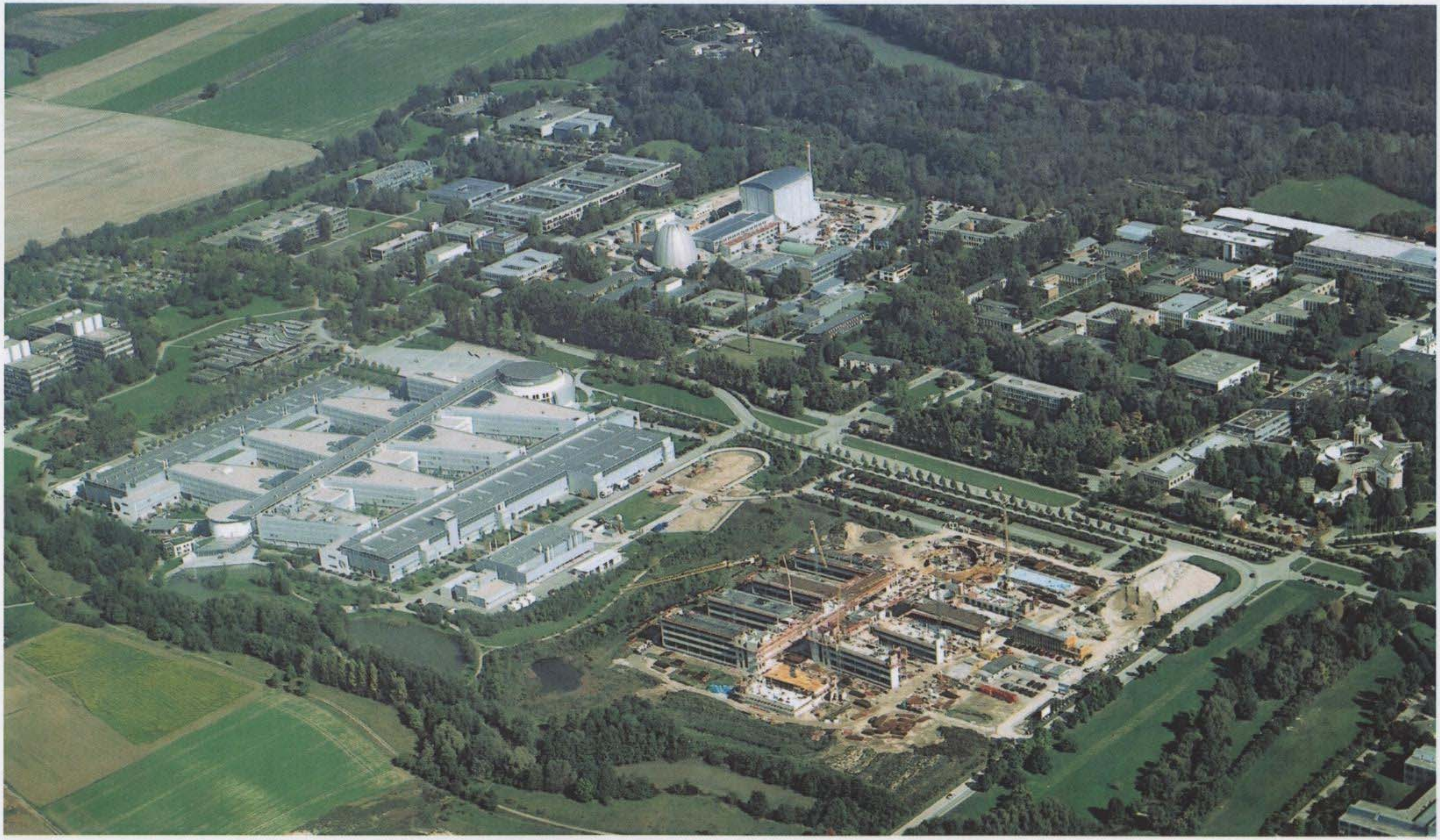
Campus in Garching

TECHNISCHE
UNIVERSITÄT
MÜNCHEN



Research at the Physics Department of TUM

condensed matter physics / materials physics:

semiconductors
magnetic materials
superconductors
polymers
granular materials
surface and interface physics

technical physics:

energy science
medical physics
opto- and nanoelectronics
nanotechnology

nuclear- and particle physics:

astro-particle physics
physics of hadrons
elementary particle physics
neutron physics
nuclear methods in interdisciplinary research

biophysics:

biomaterials
biosensors
biological functions
molecular machines

The Walter Schottky Institute (WSI)

research subjects

- materials technology and nanostructuring:
  - epitaxy, self-assembly, cleaved edge overgrowth, e-beam writing, laser processing, ...

- basic physics:
  - high mobility 2DEG‘s, magneto-transport
  - Quantum-Hall-Effect, Fractional Quantum Hall-Effect
  - quantum wires and dots
  - spin resonance
  - defect physics
  - uv-, visible-, and ir-spectroscopy

- developments for novel applications:
  - semiconductor lasers
  - quantum devices
  - spintronics
  - quantum information technology
  - photovoltaics
  - biosensors

Nanotechnology: … quo vadis?

Martin Stutzmann

WALTER SCHOTTKY INSTITUT
TECHNISCHE UNIVERSITÄT MÜNCHEN

There's Plenty of Room at the Bottom

An Invitation to Enter a New Field of Physics

by Richard P. Feynman

This transcript of the classic talk that Richard Feynman gave on December 29th 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech) was first published in the February 1960 issue of Caltech's *Engineering and Science*, which owns the copyright. It has been made available on the web at http://www.zyvex.com/nanotech/feynman.html with their kind permission.

…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...

…In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction…

…The biological example of writing information on a small scale has inspired me to think of something that should be possible… Consider the possibility that we too can make a thing very small which does what we want---that we can manufacture an object that maneuvers at that level! …

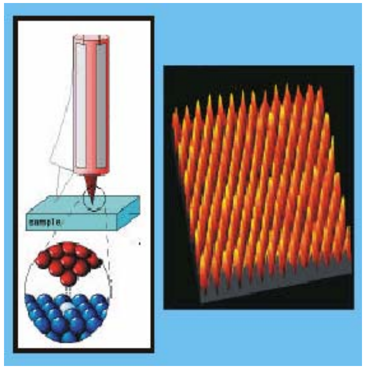
…There may even be an economic point to this business of making things very small…

…I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously, drilling holes, stamping parts, and so on…

…We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc…

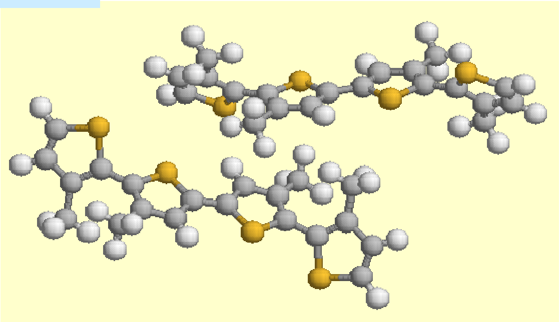
…But it is interesting that it would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Give the orders and the physicist synthesizes it…

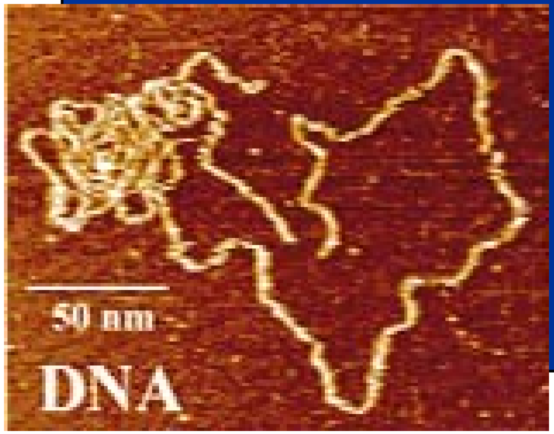
2006: „Nano“ is everywhere…



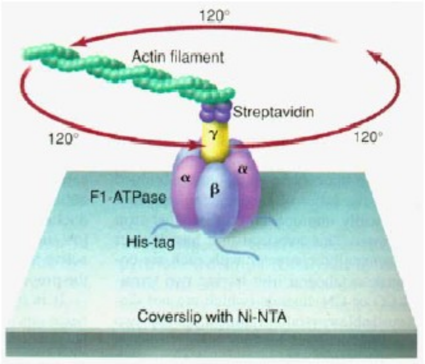
Physics

Chemistry

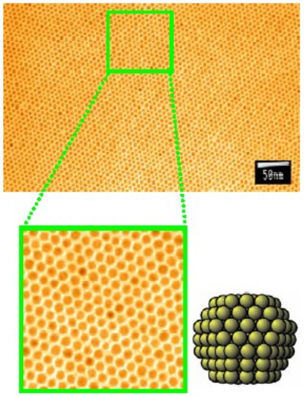


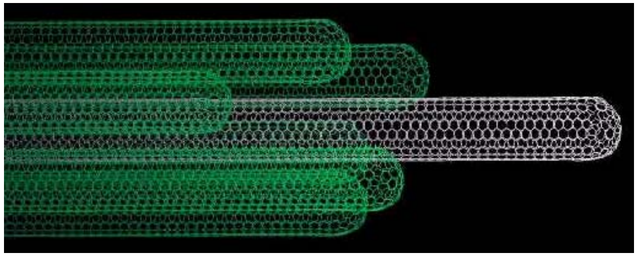


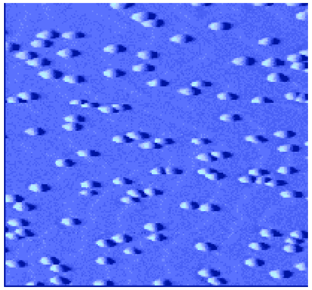
Biology



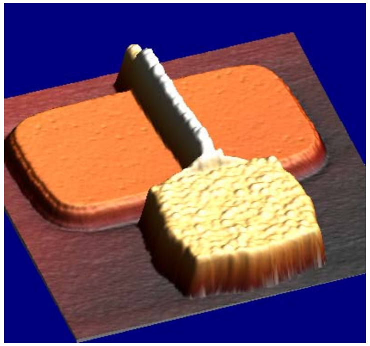
Materials

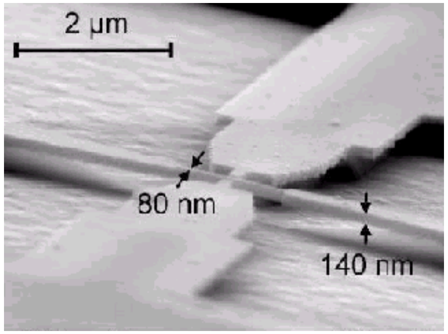




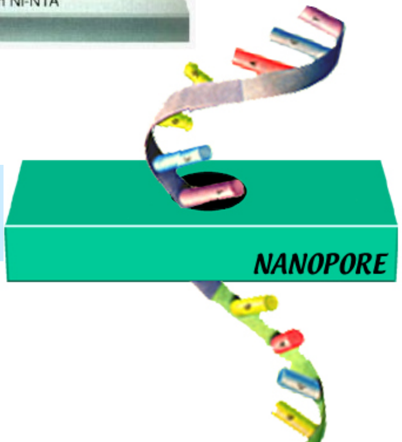


Technology

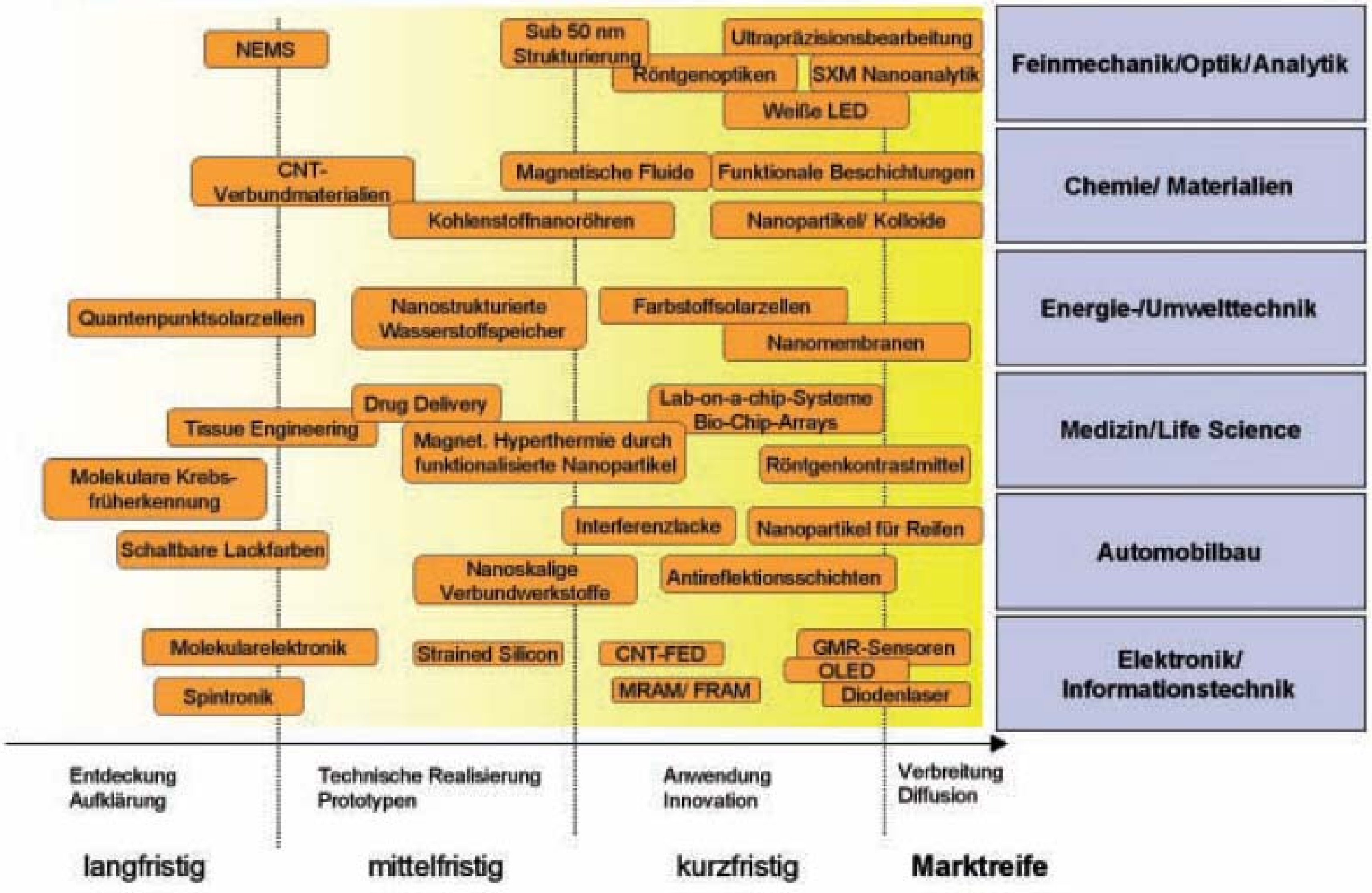




Medical

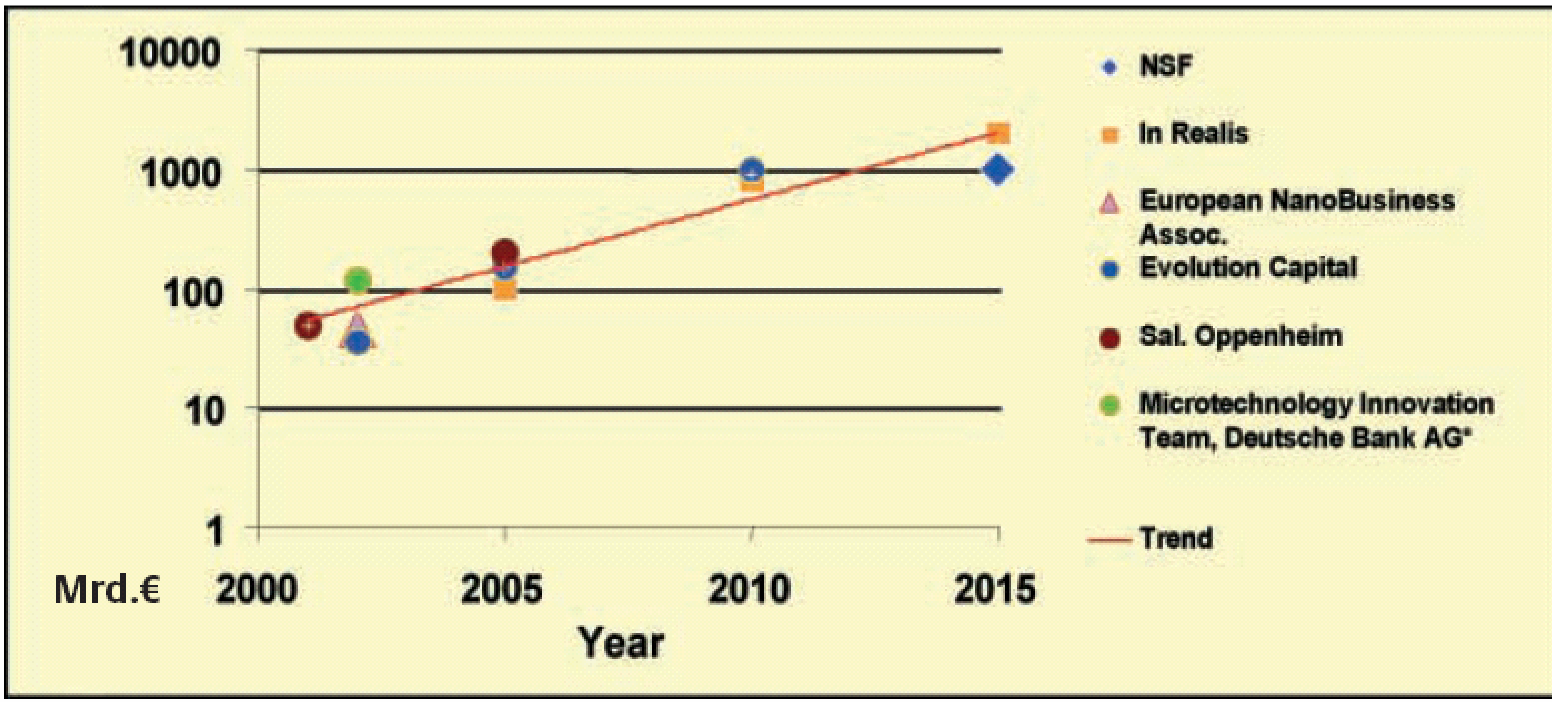


Entwicklungsstand und Anwendungsfelder der Nanotechnologie

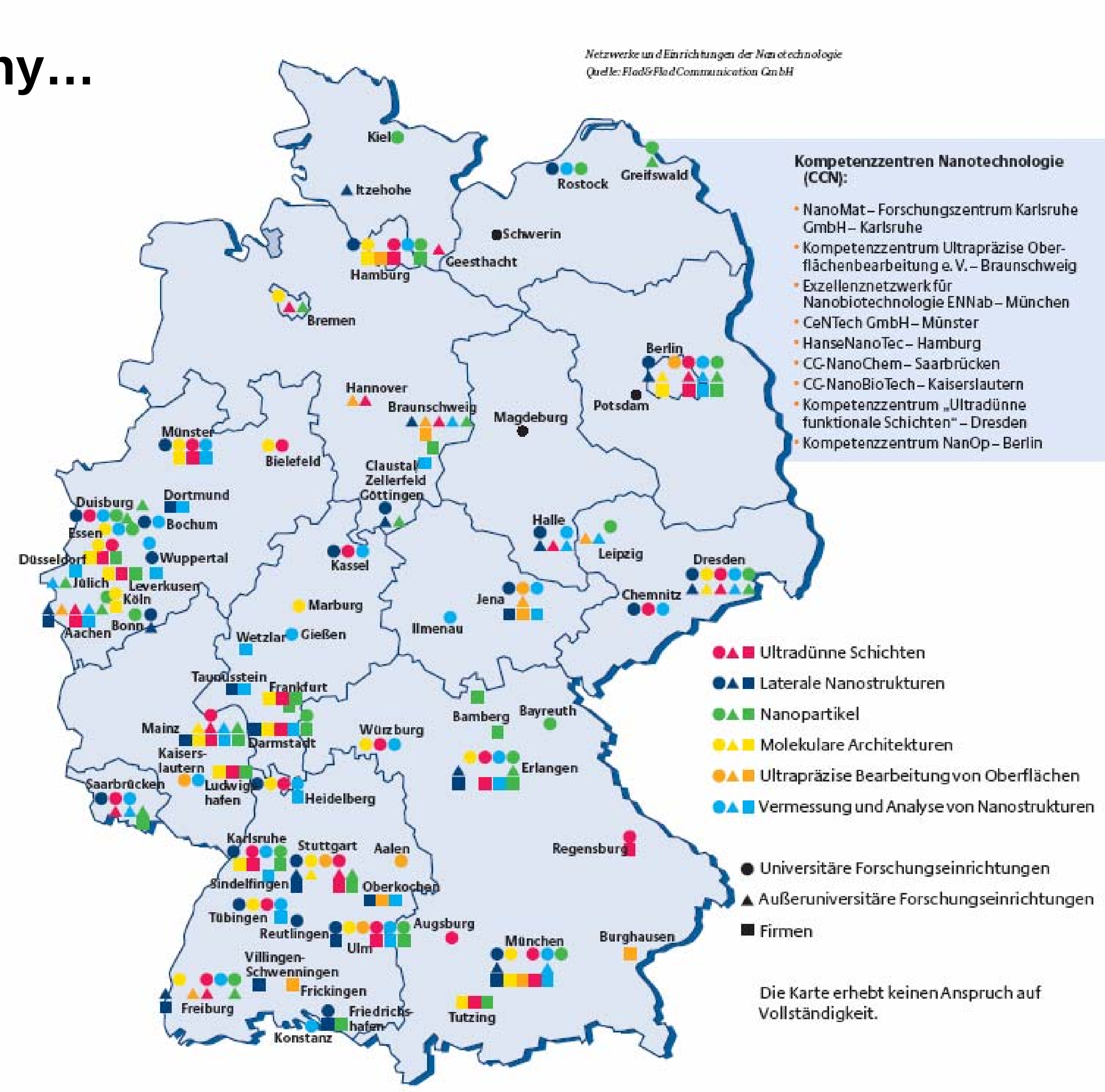


The economical side…

Aussagen zum weltweiten Marktvolumen der Nanotechnologie (in Mrd. €) aus unterschiedlichen Studien
(Quelle: Deutsche Bank, Microtechnology Innovation Team)



Nano-Germany…



But also some criticism…(even with Nobel-Prize!)

Nano-whatever: Do we really know where we are heading?

Herbert Kroemer

ECE Department and Materials Department, University of California, Santa Barbara, CA 93106, USA.

…My skepticism pertains to the unbelievable hype that has arisen, during the last decade, about the "nano-whatever" field, a hype that exceeds anything I have encountered during my fifty years in solid-state physics and technology… Much of the hype is being generated by outsiders, not actually involved in these three areas, and basically clueless about how the process from science and technology actually works, but simply wishing to profit from the development….

…What is *not* acceptable—and what we must refrain from doing—is an attempt to justify the research by promising credibility-stretching mythical improvements in *existing* applications…

The challenges of Nanotechnology:

• **Materials preparation and subsequent nano-structuring („top down“)**

• **Controlled synthesis („bottom up“)**

• **Growth by self-assembly („let‘s see what we have got on the average“)**

• **Suitable analytical methods („look what we really have got“)**

• **Controlled nano-assembly („ really know what you will get“)**

The Prophet of „top down“ Microelectronics: Gordon Moore (1960)

The experts look ahead

Cramming more components onto integrated circuits

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

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

The author

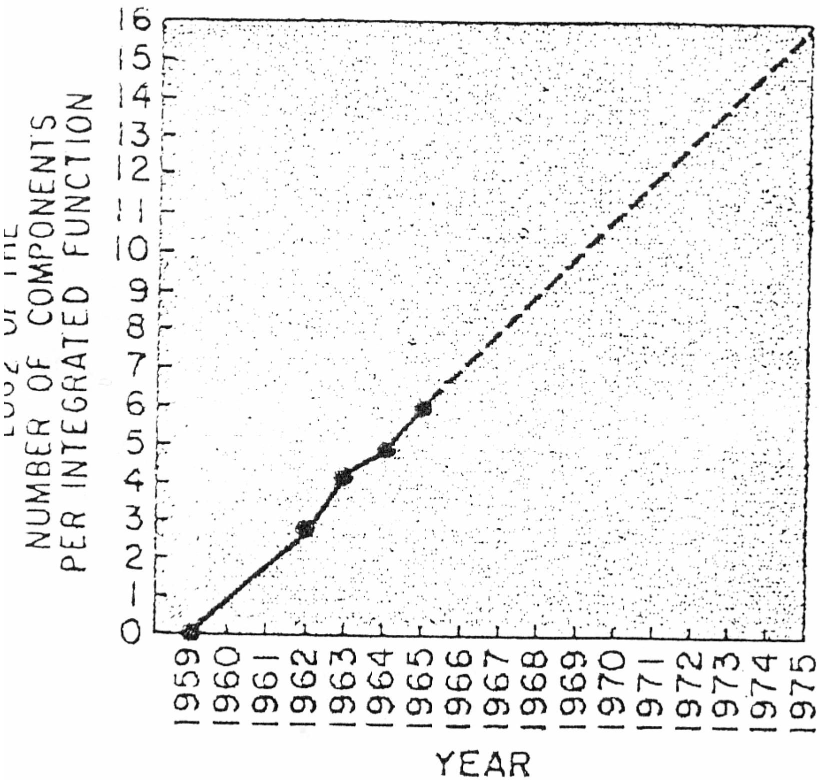
Dr. Gordon E. Moore is one of the new breed of electronic engineers, schooled in the physical sciences rather than in electronics. He earned a B.S. degree in chemistry from the University of California and a Ph.D degree in physical chemistry from the California Institute of Technology. He was one of the founders of Fairchild Semiconductor and has been director of the research and development laboratories since 1959.

The future of integrated electronics is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas.

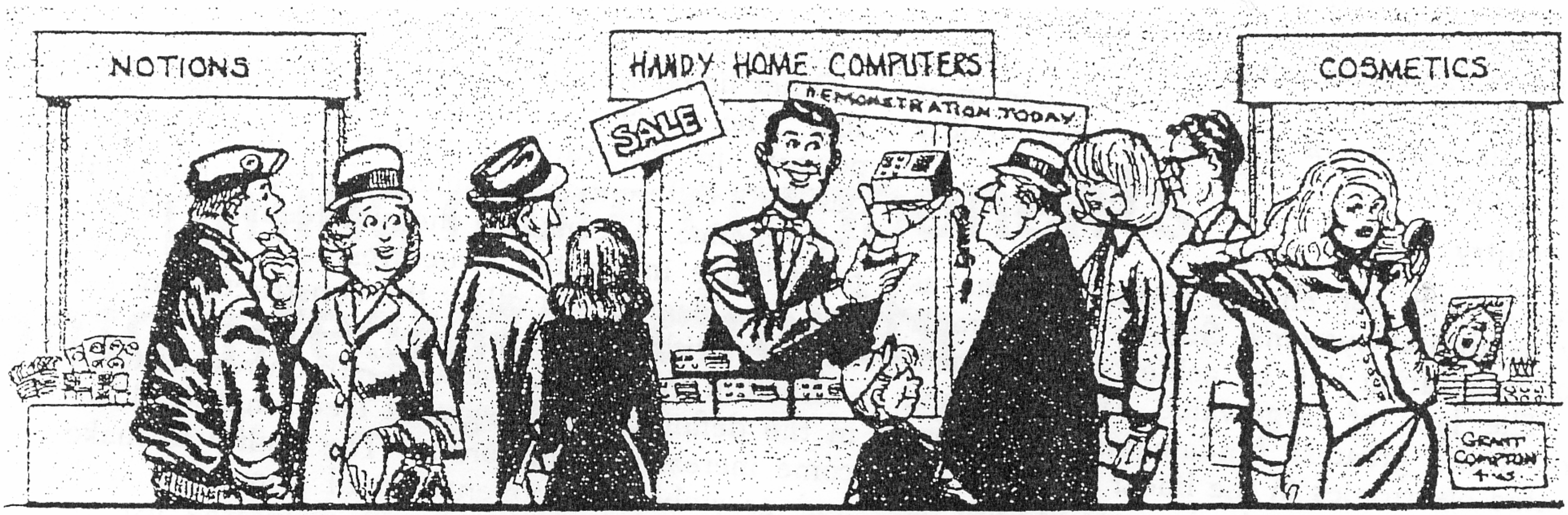
Integrated circuits will lead to such wonders as home computers—or at least terminals connected to a central computer—automatic controls for automobiles, and personal portable communications equipment. The electronic wristwatch needs only a display to be feasible today.

But the biggest potential lies in the production of large systems. In telephone communications, integrated circuits in digital filters will separate channels on multiplex equipment. Integrated circuits will also switch telephone circuits and perform data processing.

Computers will be more powerful, and will be organized in completely different ways. For example, memories built of integrated electronics may

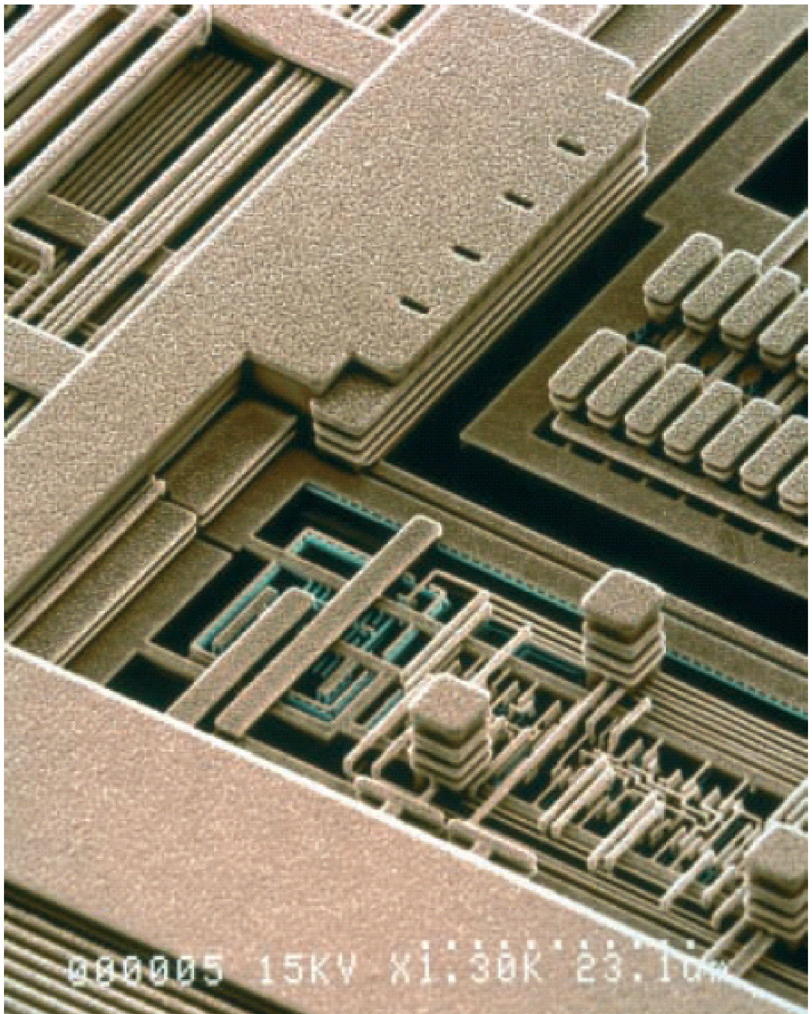


Moore‘s Vision:



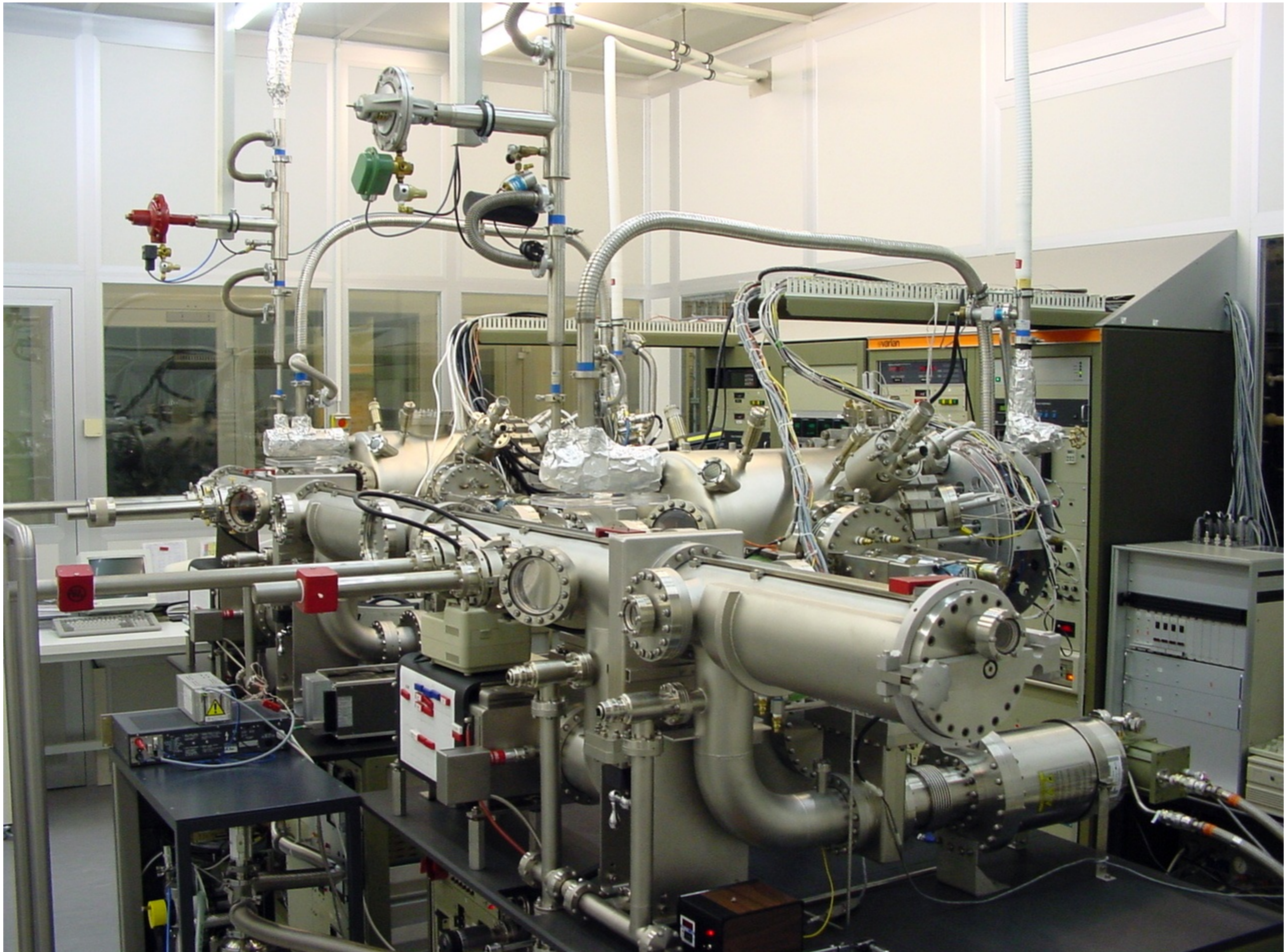
Semiconductor Nanoelectronics in 2006

3D-Elektronikaufbau
Quelle: IBM

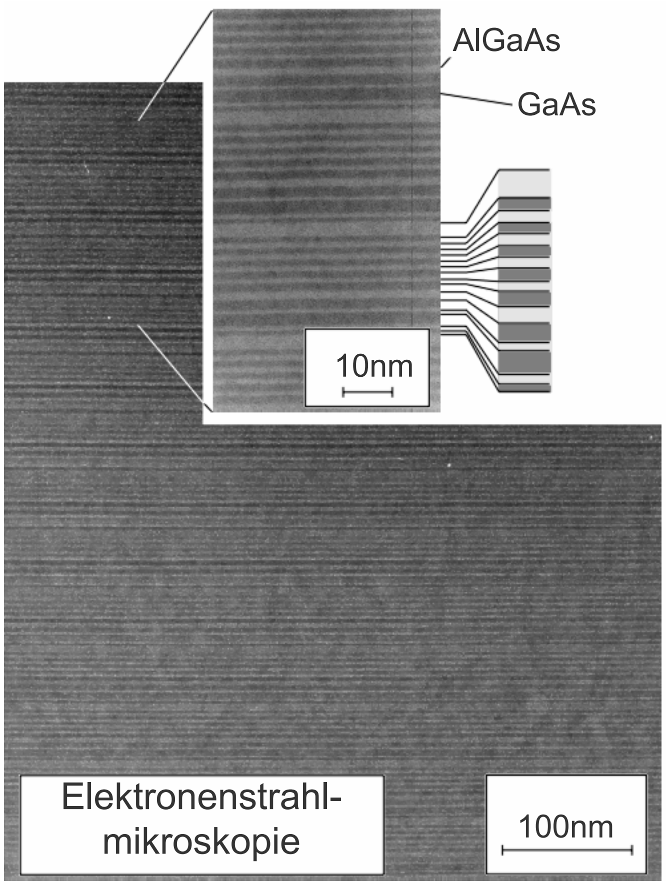


- Lateral dimensions approaching < 50 nm
- Control of layer thicknesses to less than a monolayer
- Process yields exceeding 95 %
- Complex 1D-, 2D-, und 3D-structures produced reliably
- Photolithography remains the most efficient approach for parallel processing of complex nanostructures

Material Growth by MBE:
atomic control of layer sequences

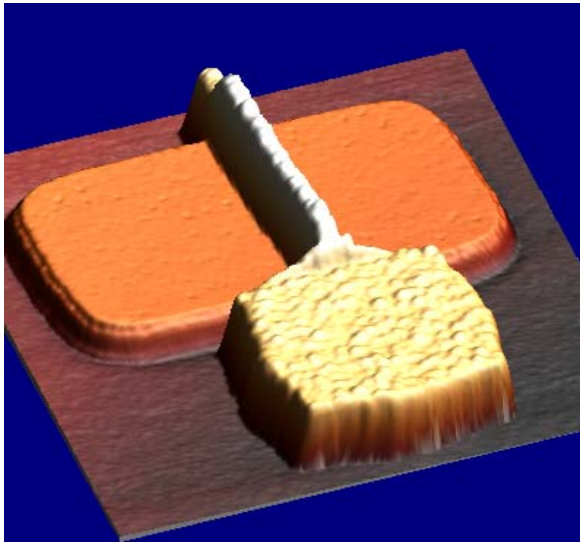


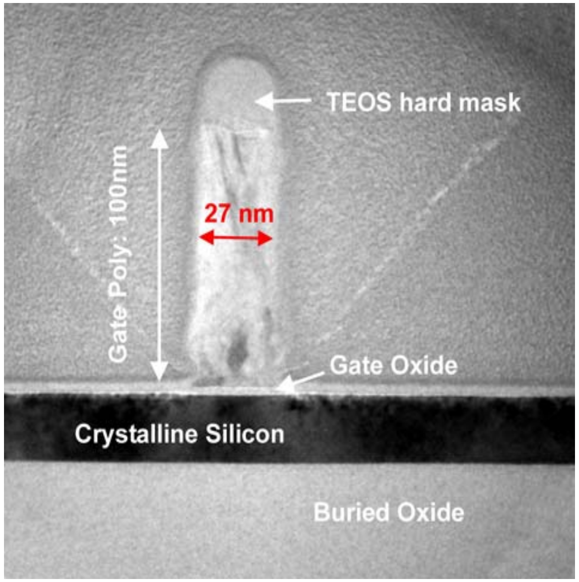
Halbleiter - Nano-Objekte (I)



- **Herstellung von 2 D Quantenfilmen und Quantentöpfen durch atomar genaue Deposition unterschiedlicher Materialien**
- **Beherrscht seit etwa 30 Jahren (Epitaxie)**
- **Grundlage der modernen Optoelektronik (Leuchtdioden, Halbleiterlaser, Sensorik, Daten-Transfer)**

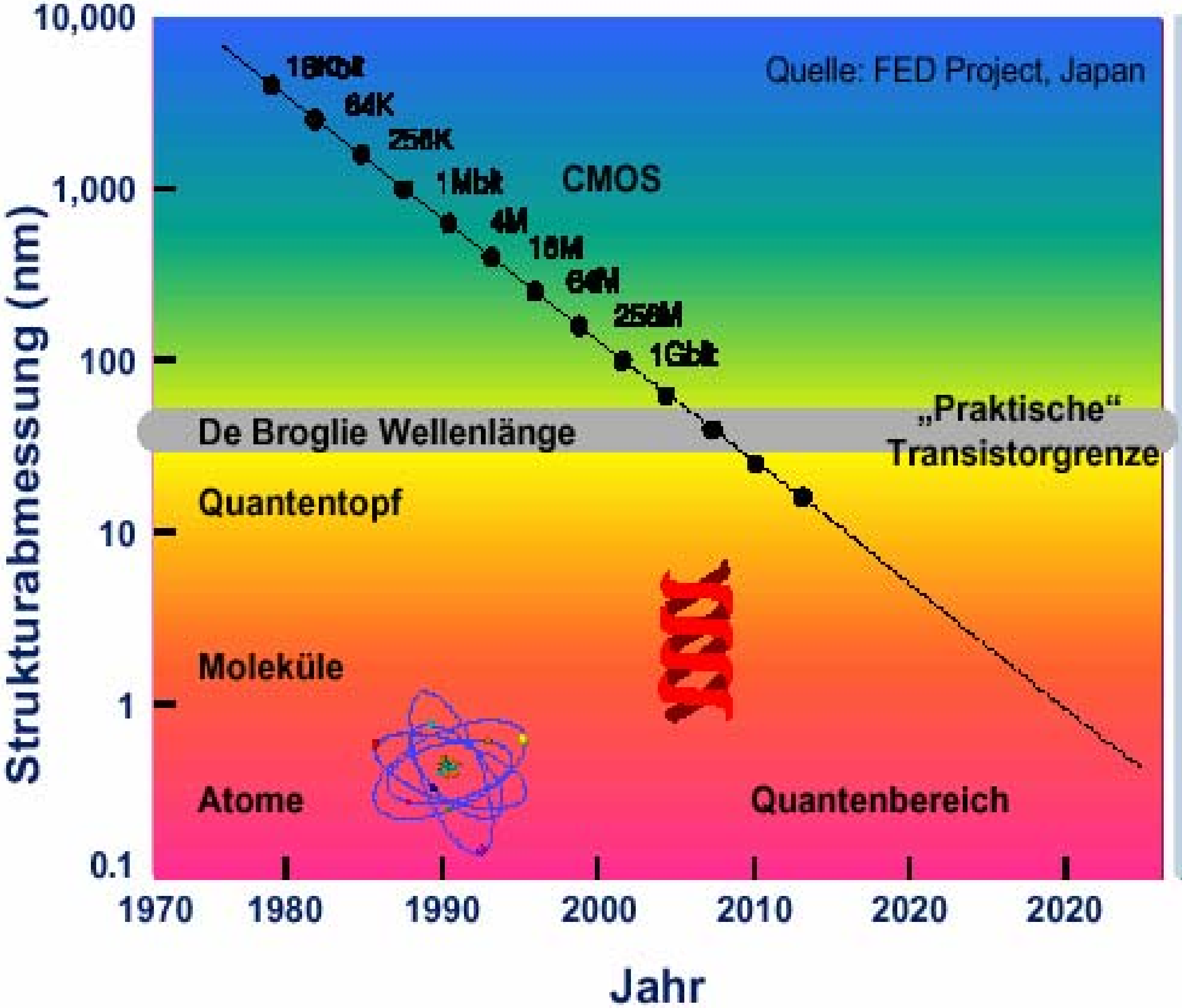
Halbleiter - Nano-Objekte (II)





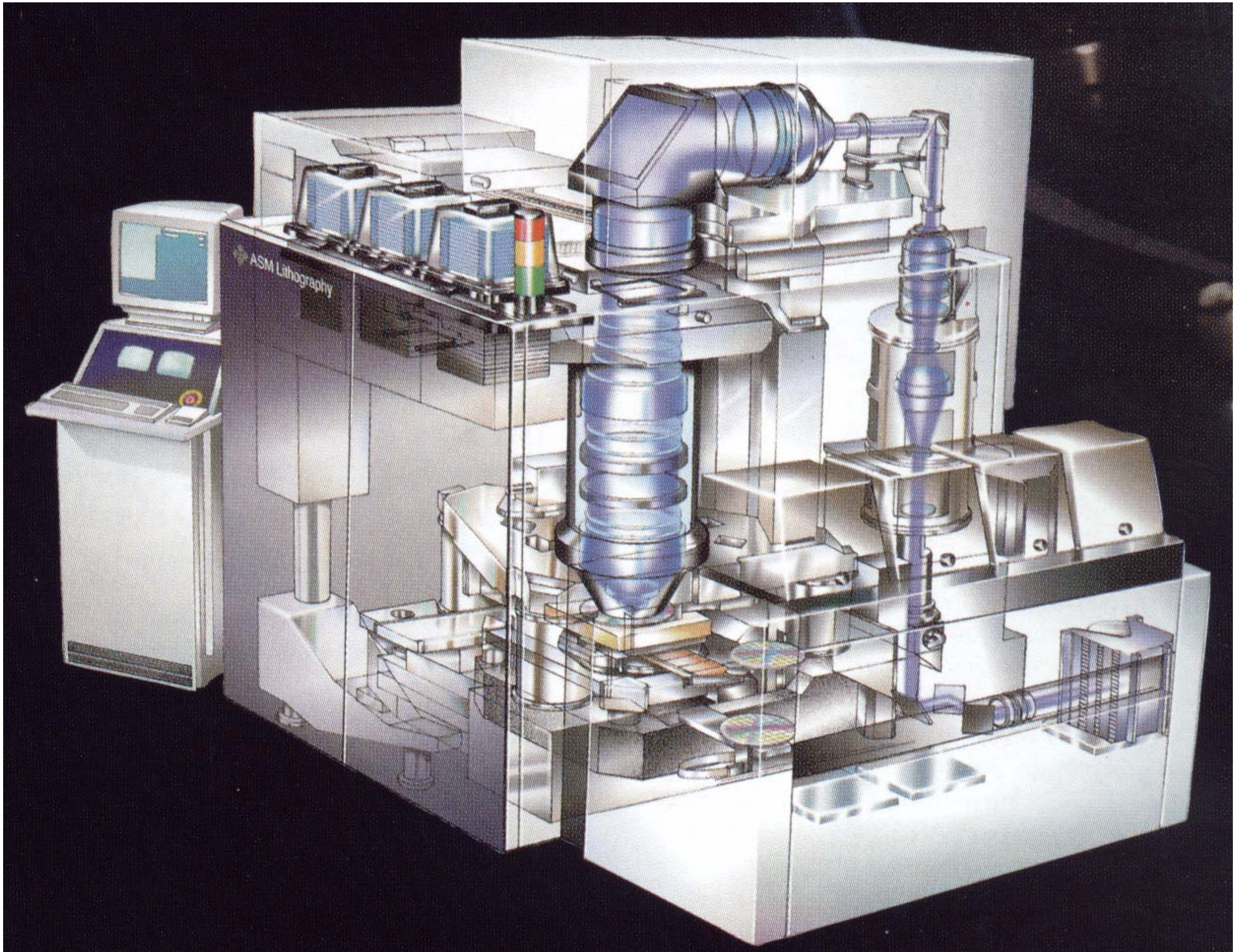
- **Die Größenordnung aktueller Bauelemente der Silizium „Mikro“-Elektronik ist bereits in der eindimensionalen Nanowelt angekommen!**
- **Die Herstellung solch kleiner Strukturen wird zunehmend schwieriger und erfordert immense Investitionen.**
- **Das Verständnis auf atomarer Ebene wird unerläßlich!**

The „Moore-Curve“: the end of „conventional“ semiconductor technology is coming closer („it just happens…“)!



- 100 nm Strukturabmessungen 2003 in Produktion
- kleinste Transistoren 50 nm
- < 50 nm neue MOS- und Quanteneffekt Bauelemente

Lithography at the 65 nm node

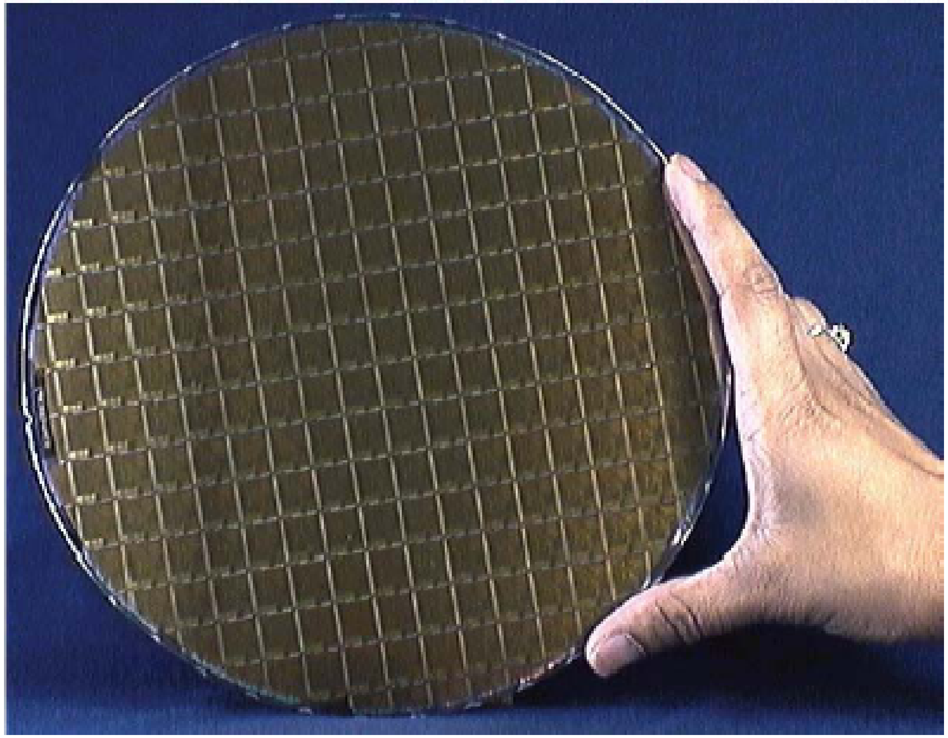


ITRS: International Technology Roadmap for Semiconductors

Table 77a Lithography Technology Requirements—Near-term UPDATED

	Year of Production	2003	2004	2005	2006	2007	2008	2009
	Technology Node		hp90			hp65		
	DRAM							
	DRAM ½ Pitch (nm)	100	90	80	70	65	57	50
	Contact in resist (nm)	130	110	100	90	80	70	60
	Contact after etch (nm)	115	100	90	80	70	65	55
WAS	Overlay	35	32	28	25	23	21	19
IS	Overlay [A]	35	32	28	25	23	21	19
	CD control (3 sigma) (nm)	12.2	11	9.8	8.6	8	7	6.1
	MPU							
	MPU/ASCI Metal 1 (M1) ½ pitch (nm)	120	107	95	85	76	67	60
	MPU ½ Pitch (nm) (uncontacted gate)	107	90	80	70	65	57	50
WAS	MPU gate in resist (nm)	◆ 65	53	45	40	35	32	28
IS	MPU gate in resist (nm)	65	◆ 53	45	40	35	32	28
	MPU gate length after etch (nm)	45	37	32	28	25	22	20
	Contact in resist (nm)	130	122	100	90	80	75	60
	Contact after etch (nm)	120	107	95	85	76	67	60
WAS	Gate CD control (3 sigma) (nm)	◆ 4.0	3.3	2.9	2.5	2.2	2	1.8
IS	Gate CD control (3 sigma) (nm)	◆ 4.0	◆ 3.3	2.9	2.5	2.2	2	1.8
	ASIC/LP							
	ASIC ½ Pitch (nm) (uncontacted gate)	107	90	80	70	65	57	50
	ASIC/LP gate in resist (nm)	90	75	65	53	45	40	36
WAS	ASIC/LP gate length after etch (nm)	65	53	45	37	32	28	25
IS	ASIC/LP gate length after etch (nm)	65	◆ 53	45	37	32	28	25
	Contact in resist (nm)	130	122	100	90	80	75	60
	Contact after etch (nm)	120	107	95	85	76	67	60
	CD control (3 sigma) (nm)	5.8	4.7	4	3.3	2.9	2.5	2.2
	Chip size (mm^2)							
	DRAM, introduction	485	383	568	419	662	449	356
	DRAM, production	139	110	82	122	97	131	104
	MPU, high volume at introduction	280	280	280	280	280	280	280
	MPU, high volume at production	140	140	140	140	140	140	140
	MPU, high performance	310	310	310	310	310	310	310
	ASIC	704	704	704	704	704	704	704
	Minimum field area	704	704	704	704	704	704	704
	Wafer size (diameter, mm)	300	300	300	300	300	300	300

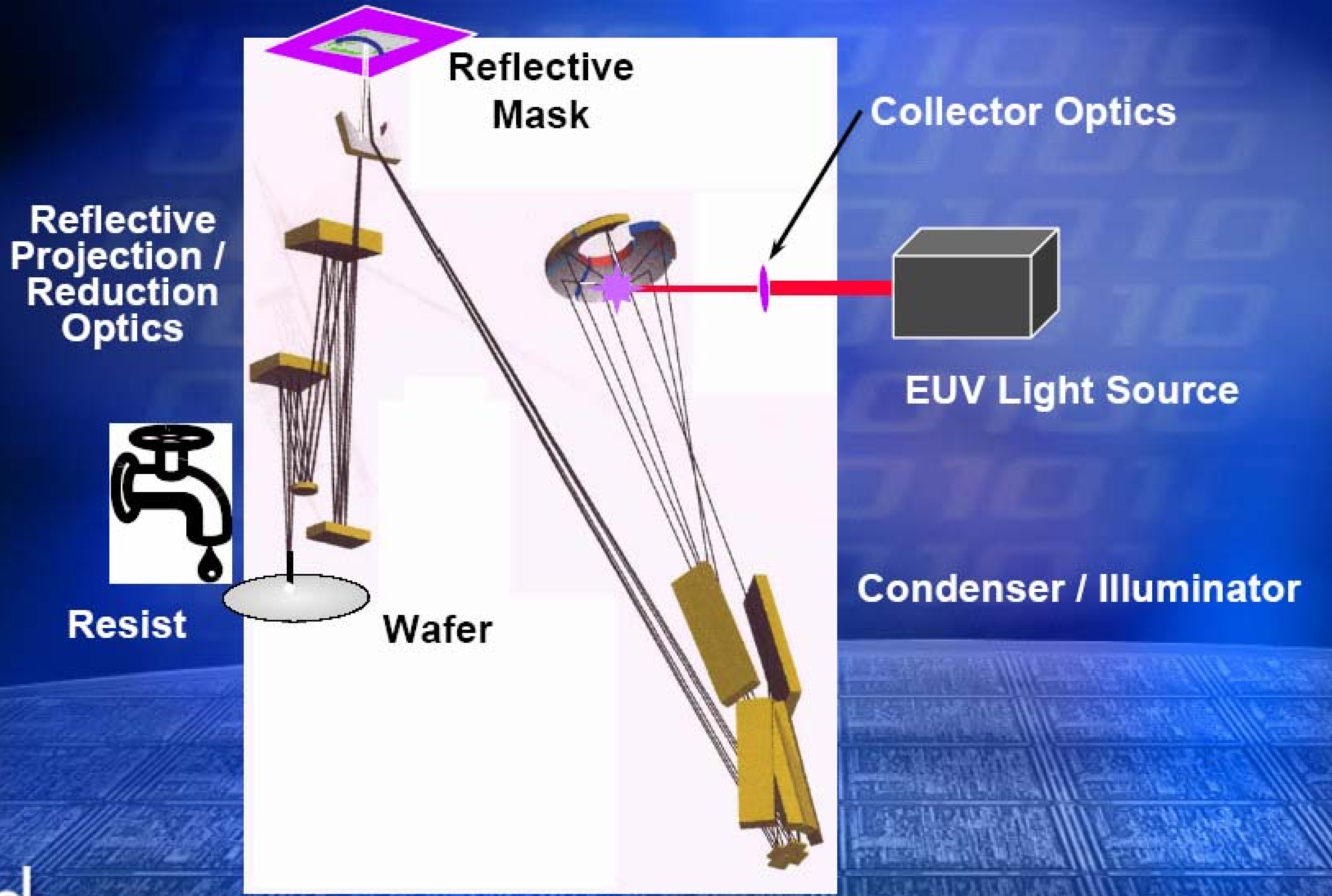
Manufacturable solutions exist, and are being optimized
Manufacturable solutions are known
Interim solutions are known ◆
Manufacturable solutions are NOT known



10 billion components
8 inch diameter

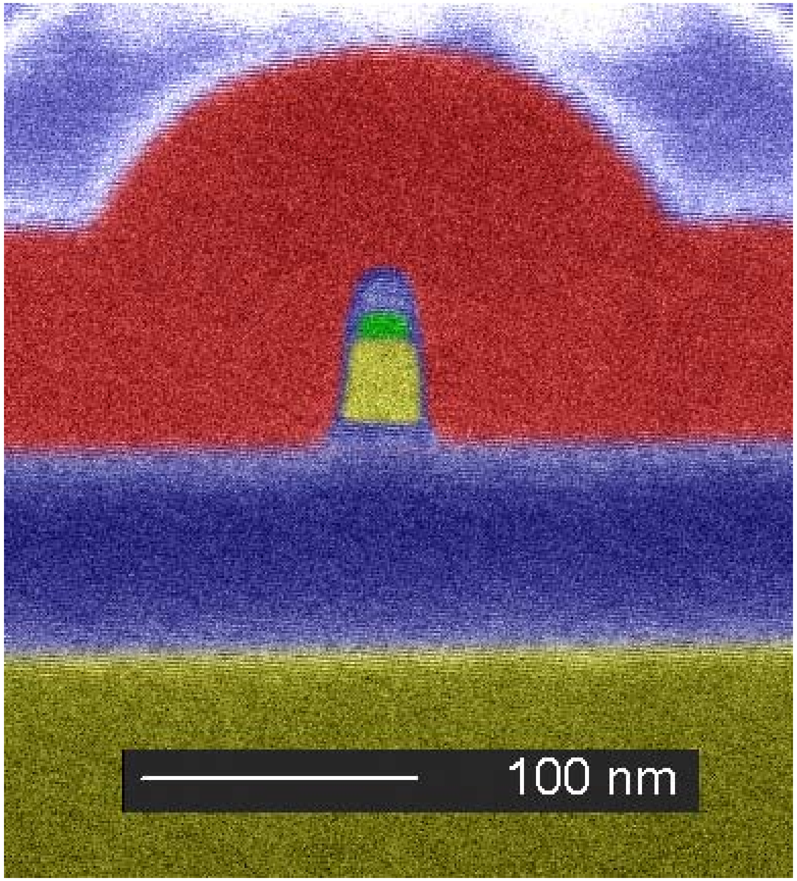
6 billion people
8000 mile diameter

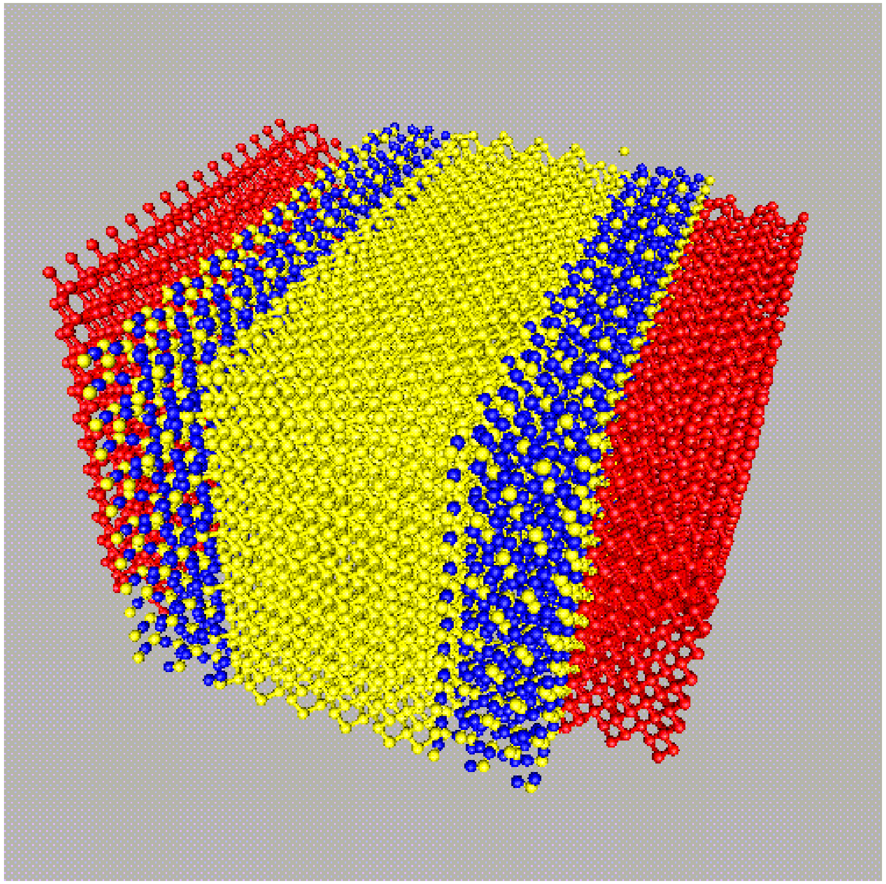
Light path in an EUV exposure tool



EUVL-Stepperanlage für die Chipherstellung
Quelle: Carl Zeiss SMT AG

Simulation of Nano-Transistors: understanding the electronic and device properties on an atomic level. Single atom defects can have a big influence on nanostructure devices.

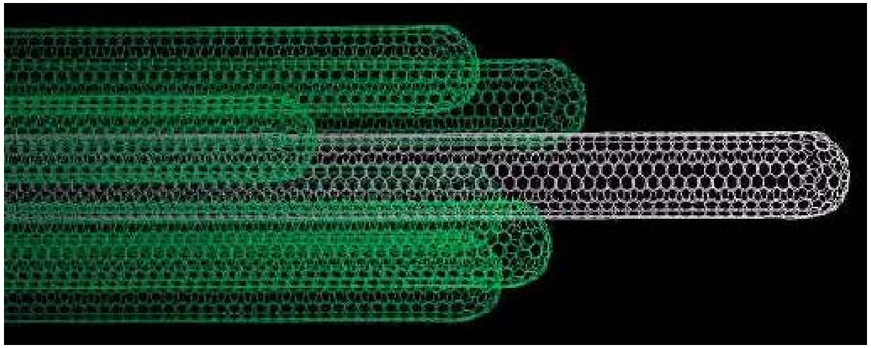




Challenges of the „top-down“ technology

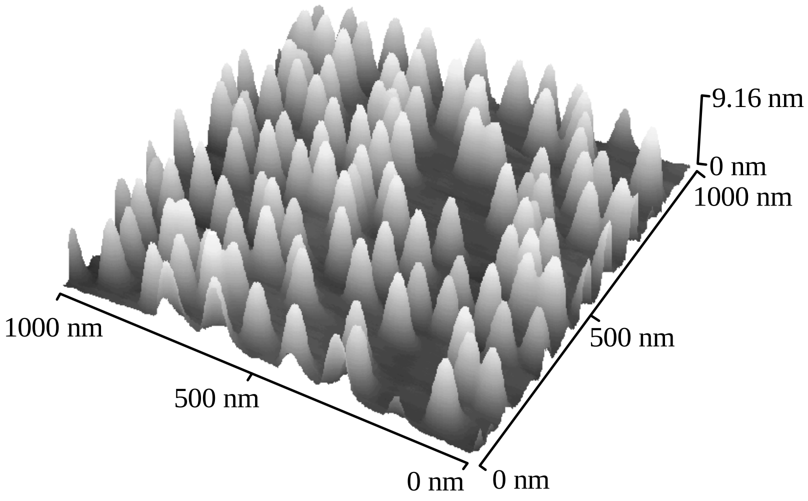
- **Going nano requires novel materials, technologies, and measurement tools.**
- **The physical limits of silicon-based nanotechnology are within reach (2015?).**
- **Only very few companies will be able to make the financial investment necessary for the next step.**

Self-organized semiconductor nanostructures: the solution?

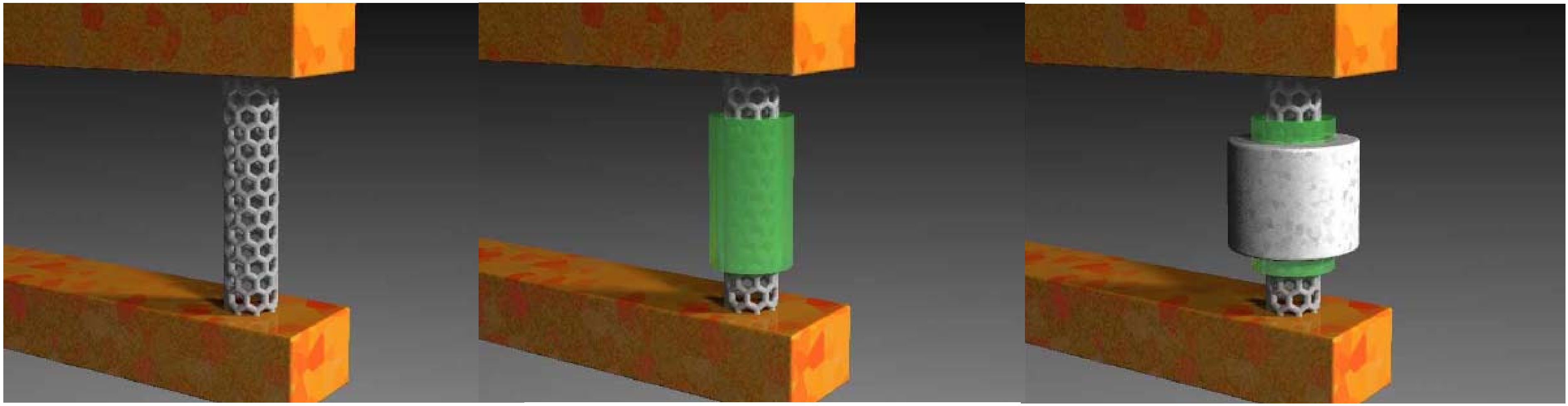


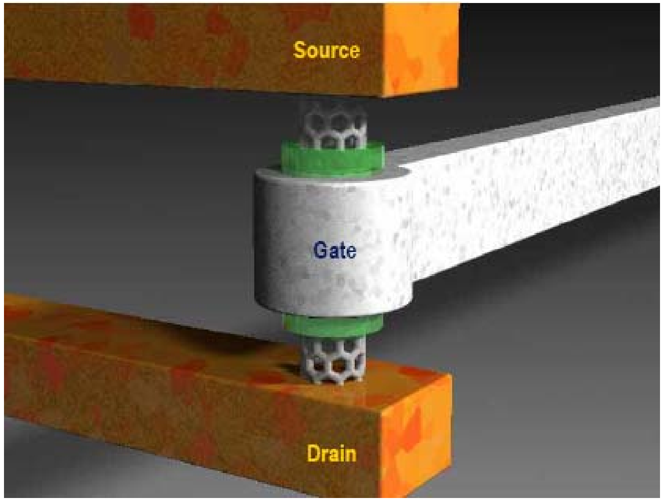
Self-organized growth of nanowires und nanodots:

Artificial atoms and wires



Vertical CNT Transistor

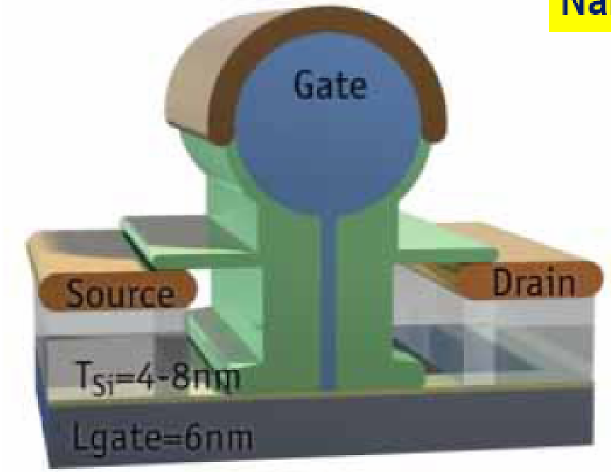


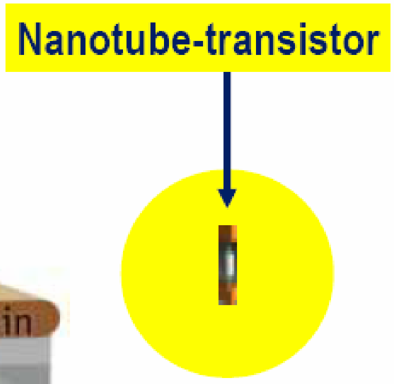


Courtesy of Infineon Technologies

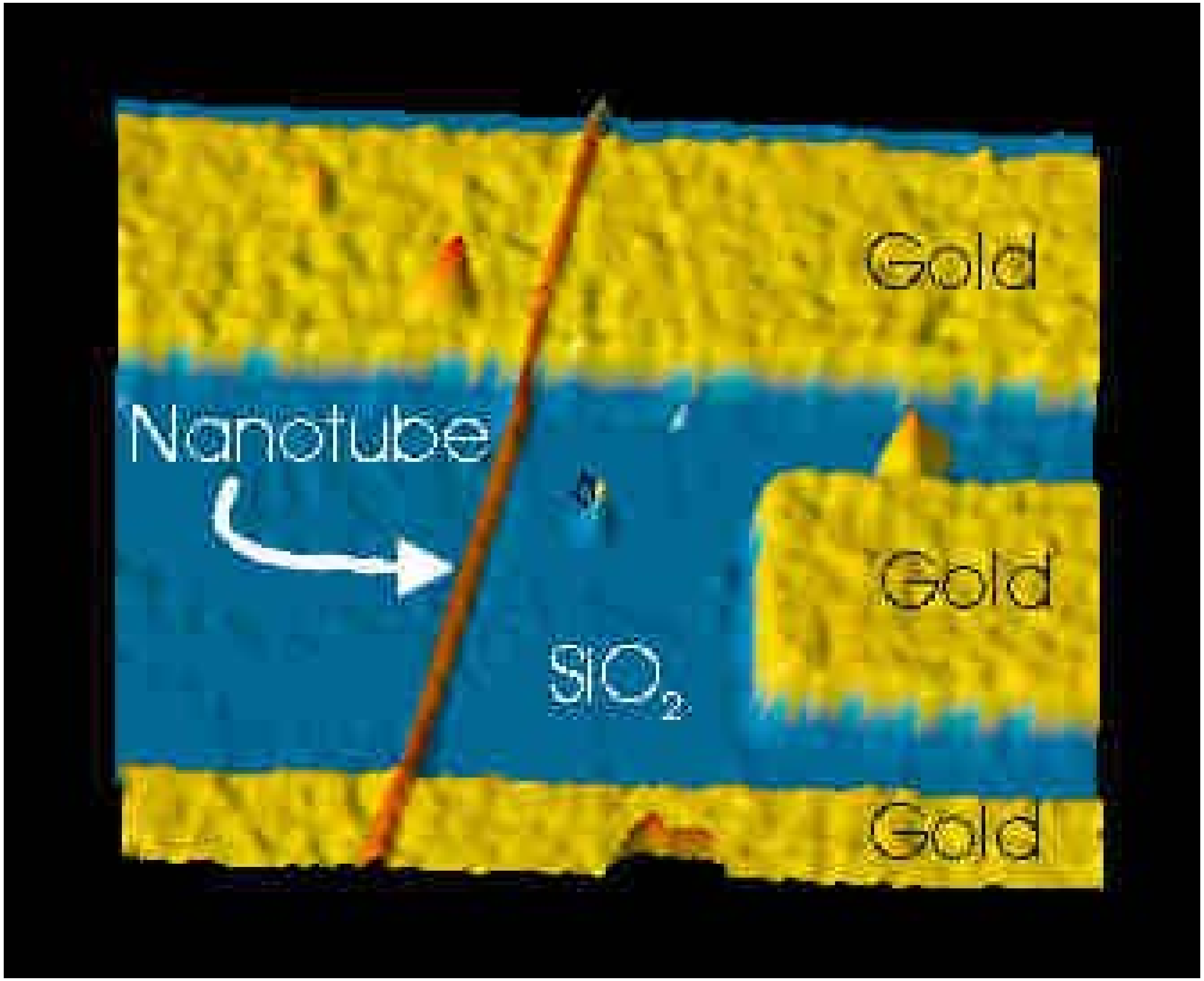
IBM unveils world's smallest transistor

09:05 Monday 9th December 2002
John G. Spooner, CNET News.com

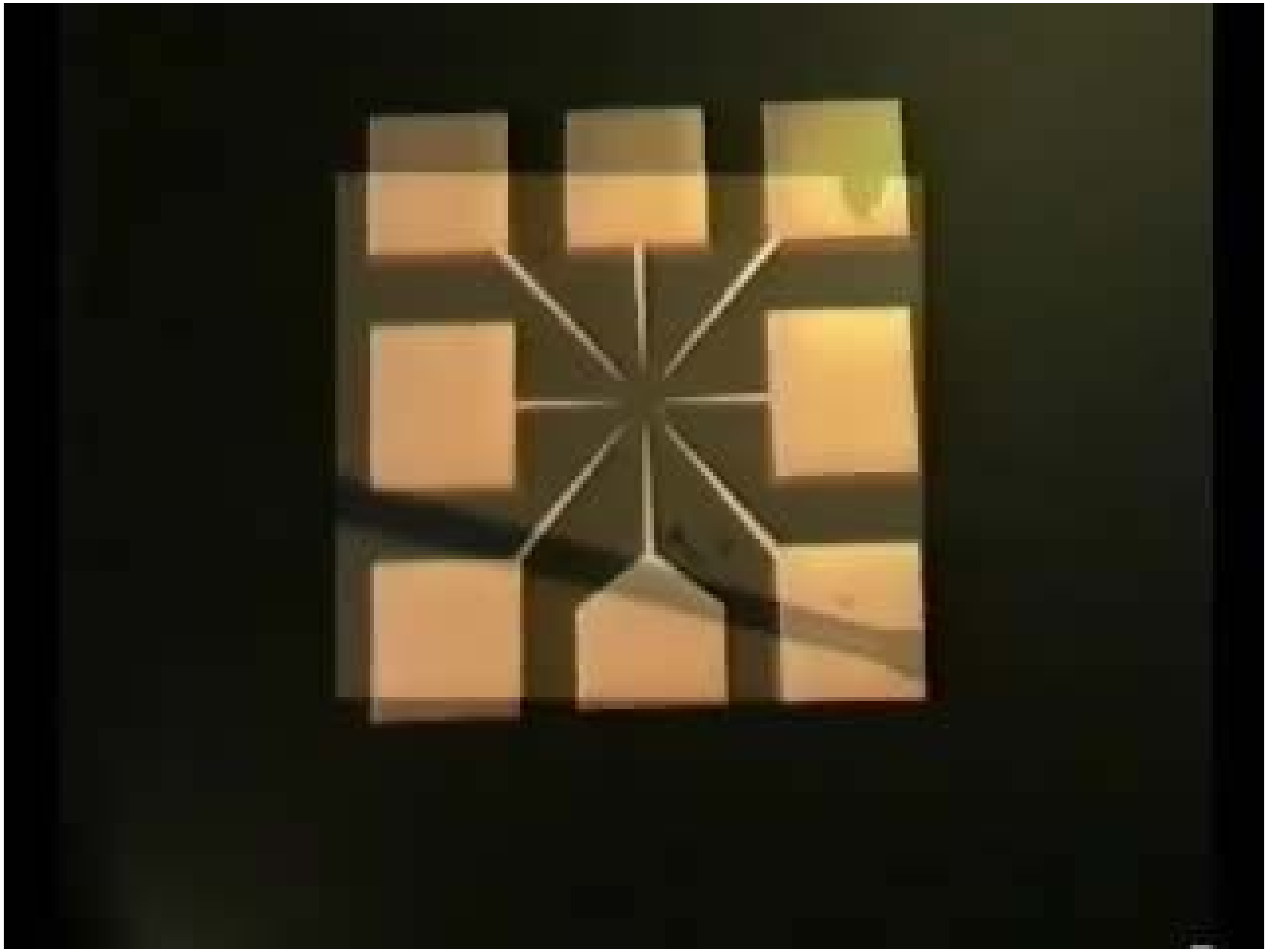




State of the art…

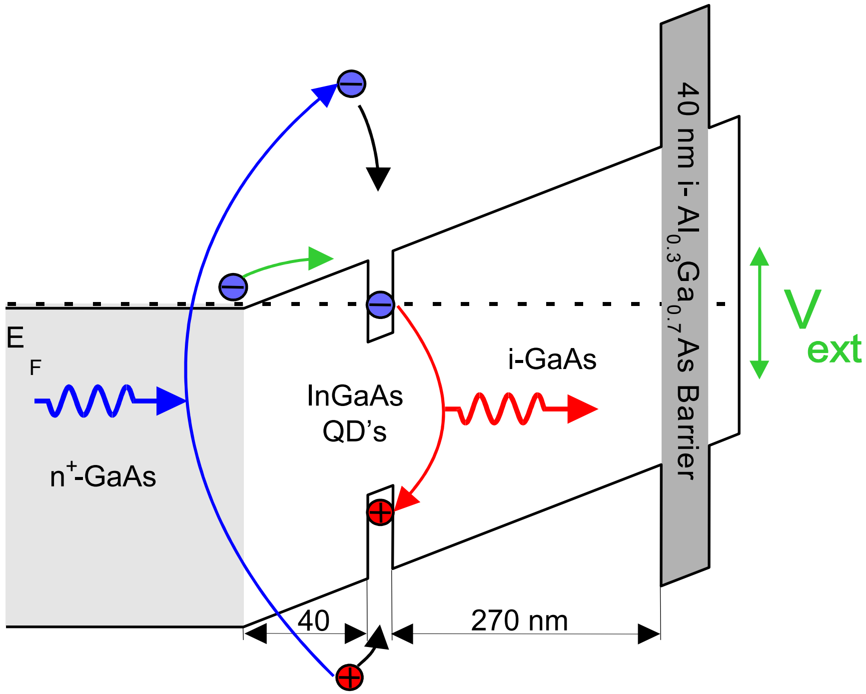


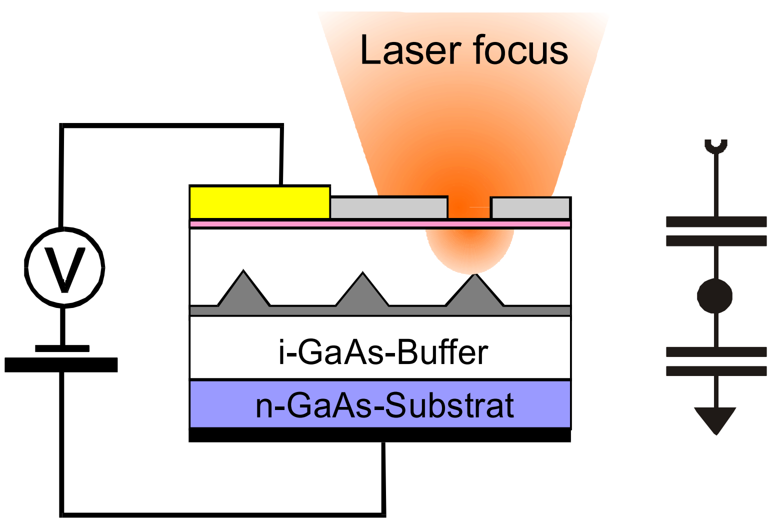
… but makes a great movie!



Single quantum dot devices

- Photoluminescence and photocurrent spectroscopy on the same QD as function of an external voltage V_{ext}





- Single electron charging from the n^+-GaAs back-contact

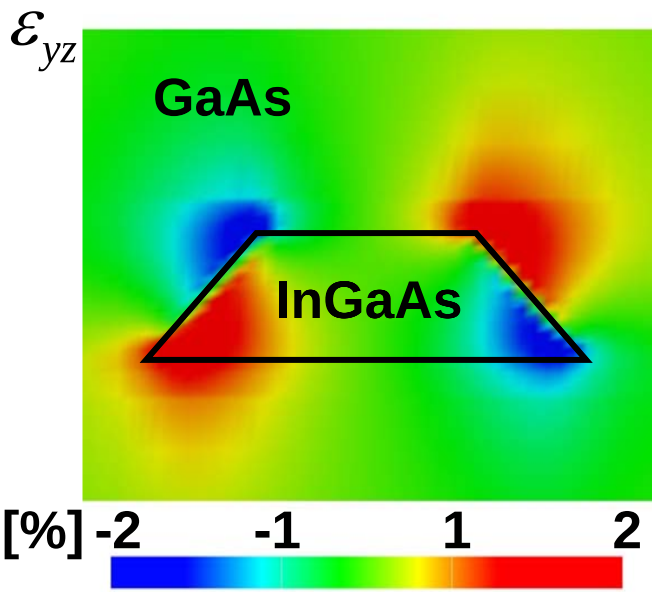
Coulomb-charging Energy:
$C_{QD} \sim 5 \times 10^{-18}$ F $\rightarrow$ $E_c \sim 20$ meV

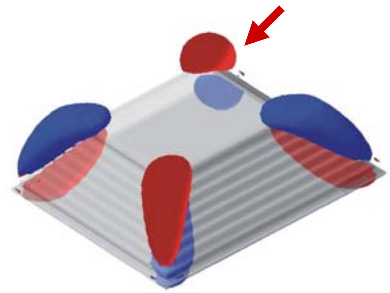
Advanced simulation tools

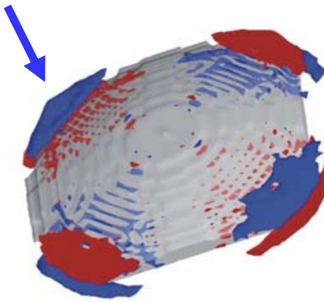
nextnano^3
next generation 3D nanodevice simulator

Strain → **piezoelectric charges**

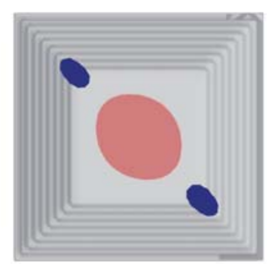
Minimization of
elastic energy in dot

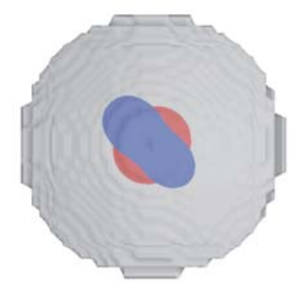






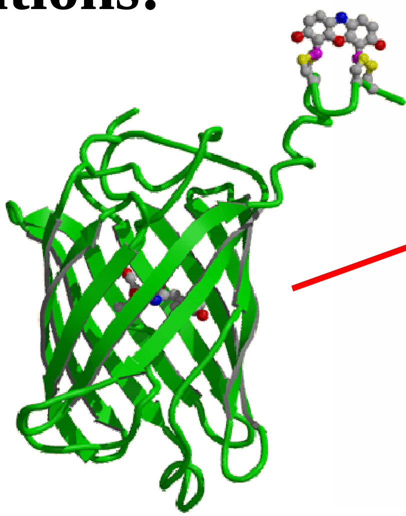
Localization of electron- und hole-wave function

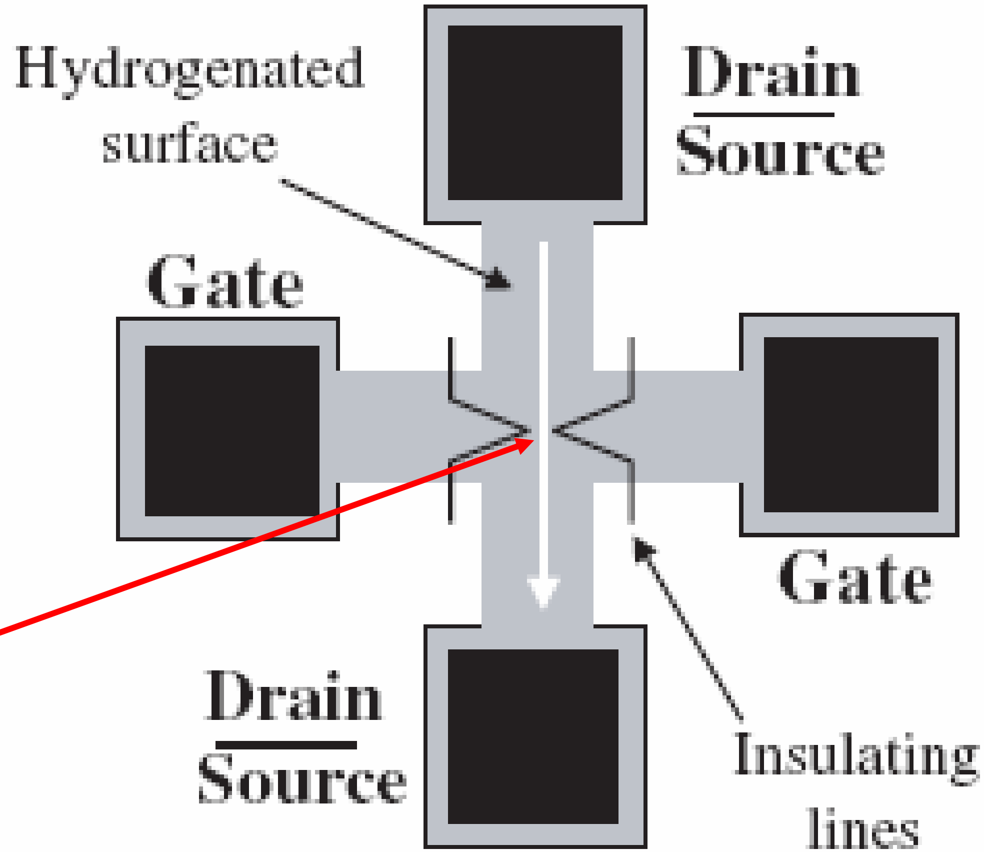




Old Materials with New Functionality

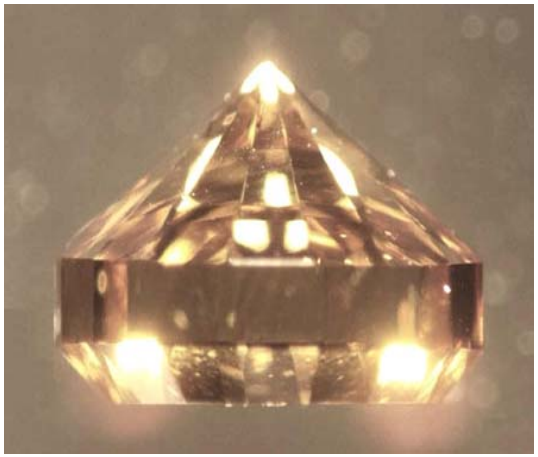
In-plane-gate transistors on diamond surfaces for biomedical applications:

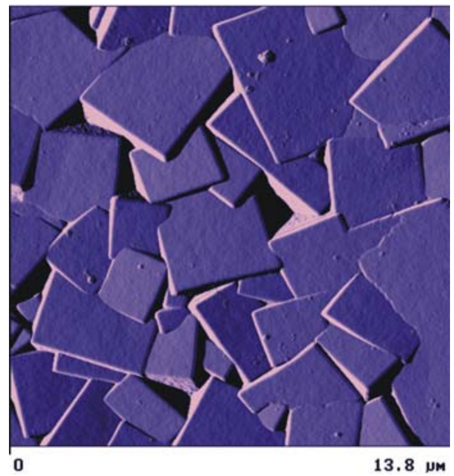


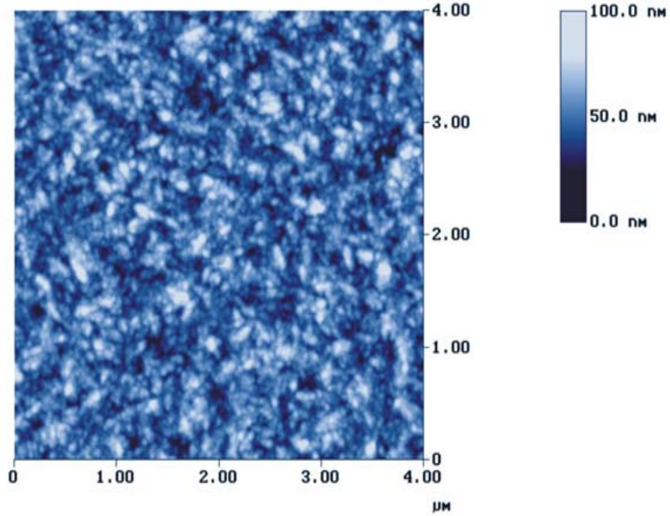


Biocompatible electronic devices with structure sizes in the 10 nm range...

Forms of Diamond grown by CVD







Single crystal:

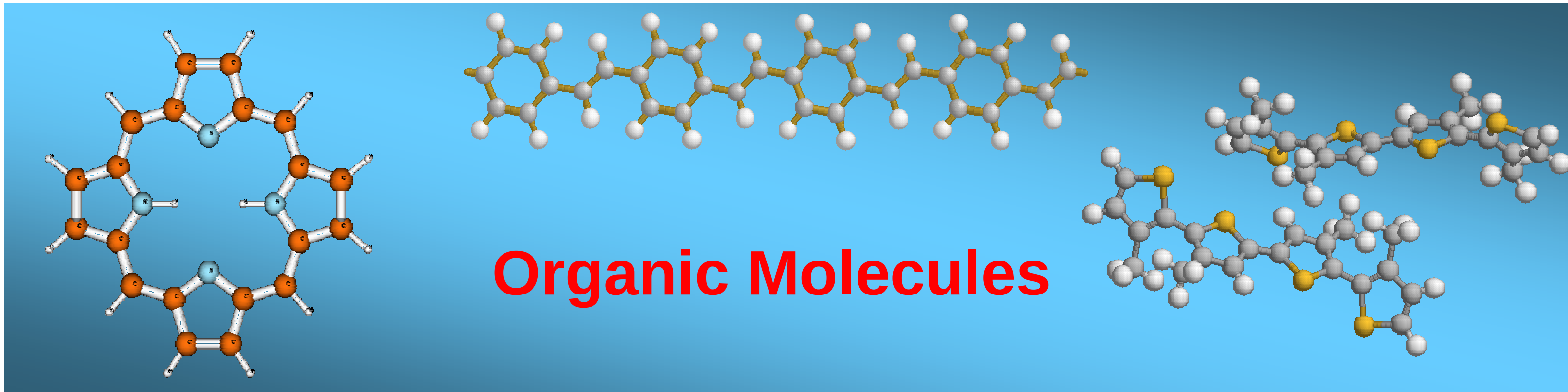
1 inch substrates by 2006 (?)

Polycrystalline:

On 6 inch substrates (Si, Ir) commercially available

Nano- or ultranano-crystalline:
available as thin film on everything…

The "bottom up" approach



Organic Material for electronics

- Electroluminescent devices
- Organic Transistors
- Organic Lasers
- Organic Solar Cells

Conventional devices with organic semiconductors

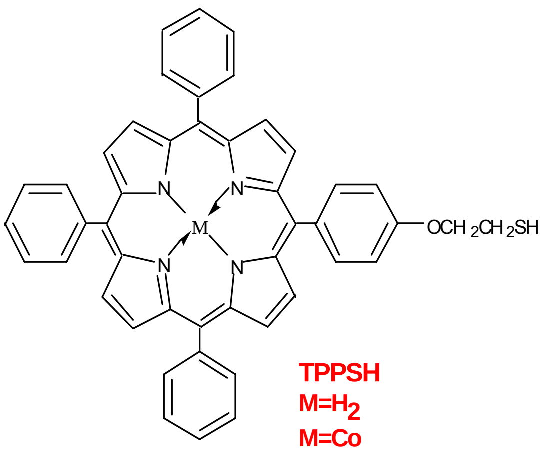
Molecular Electronics

- Diodes
- Transistors
- Memories

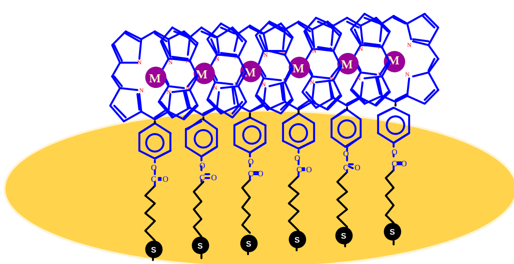
New devices with nanosize dimension

Self-assembled monolayers

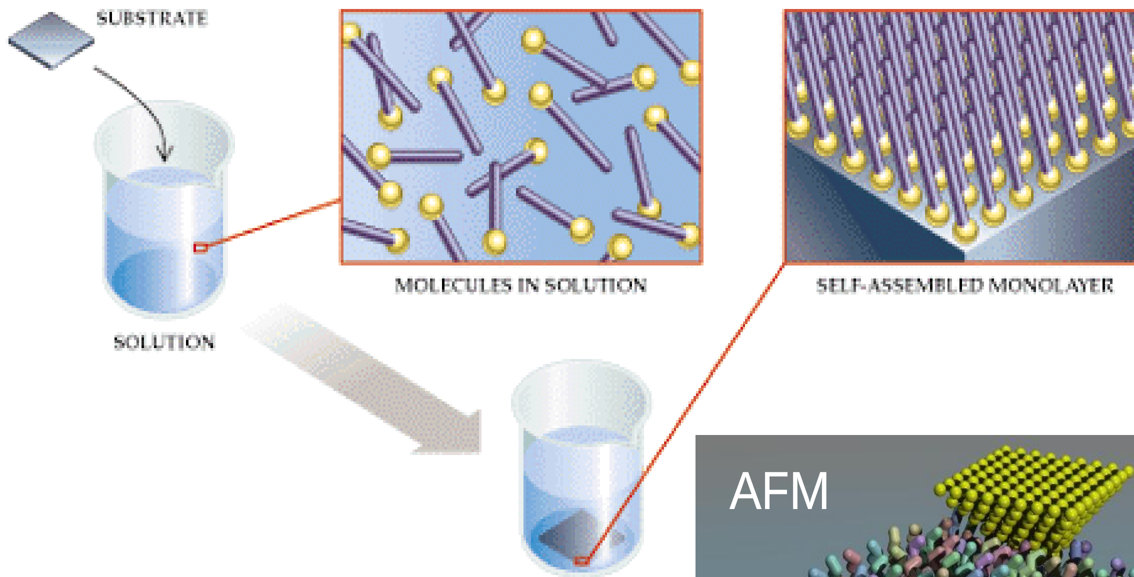
porphyrin molecules can be functionalized with thiol-derivatized chains in order to be covalently bounded onto gold surface

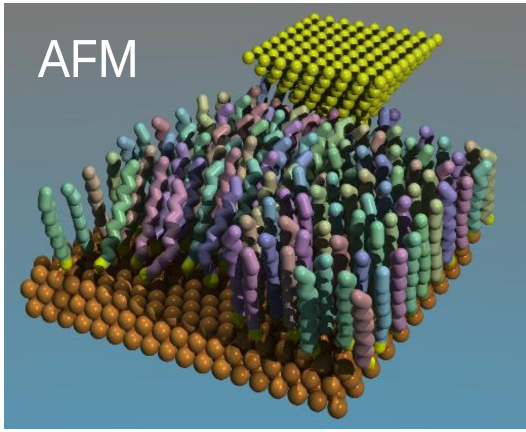


TPPSH
$M=H_2$
M=Co

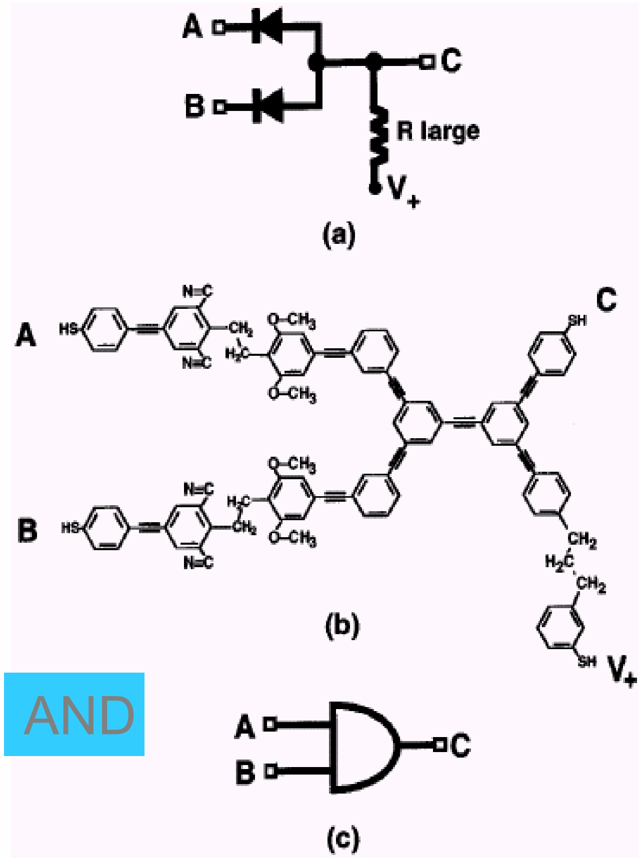


Gold surface



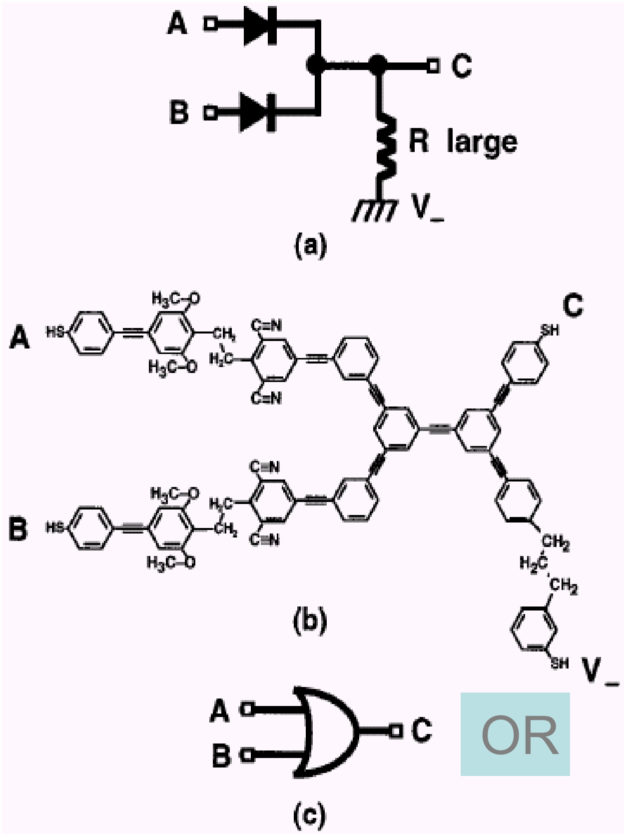


Molecular Digital Electronics



A	B	C
0	0	0
1	0	0
0	1	0
1	1	1

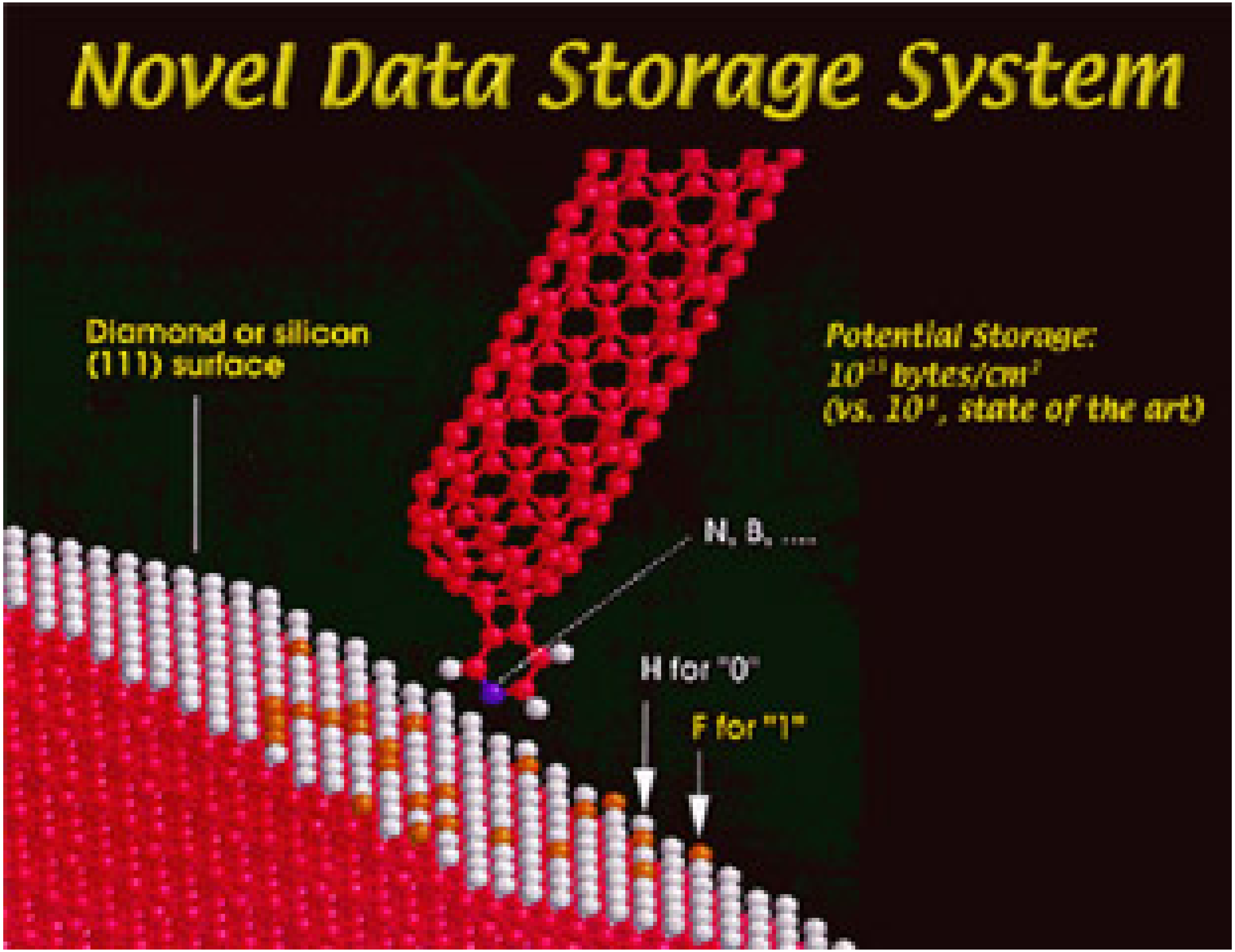
(d)



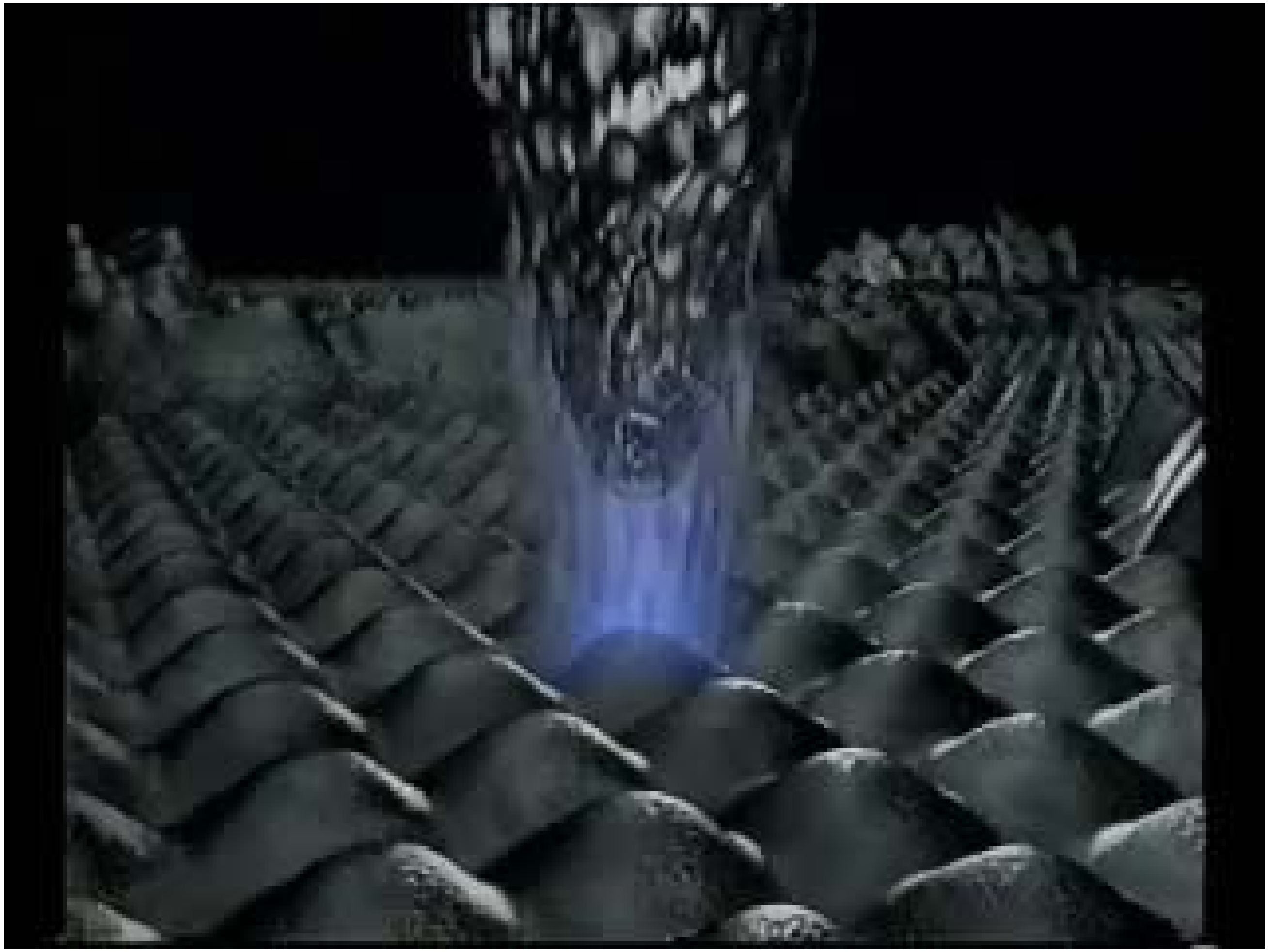
A	B	C
0	0	0
1	0	1
0	1	1
1	1	1

(d)

Data storage with atomic resolution?



Scanning Probe Systems as the central tool for nanotechnology and nanoassembly



The ultimate challenge: efficient and accurate nanoassembly