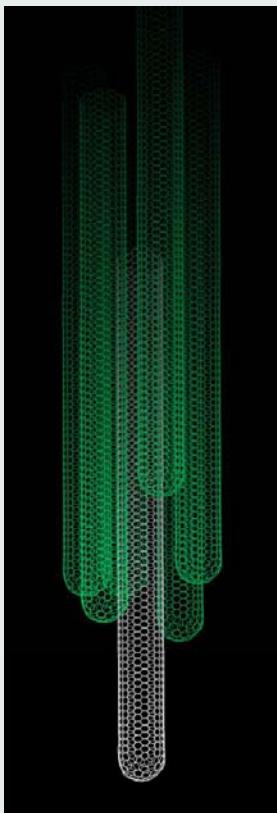
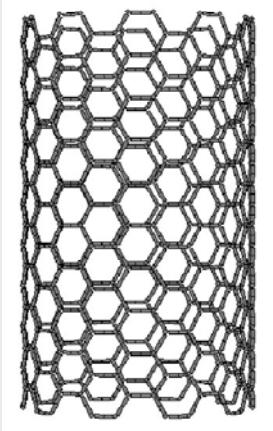


Carbon Nanotubes - CNTs

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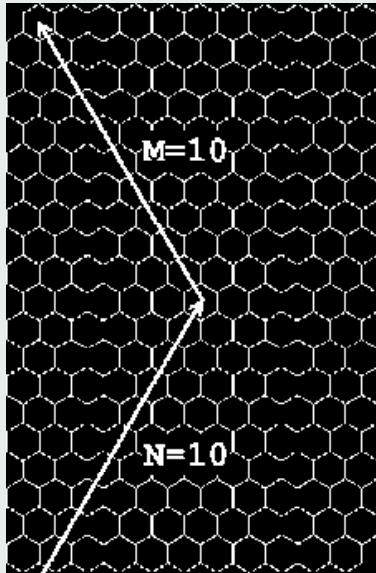
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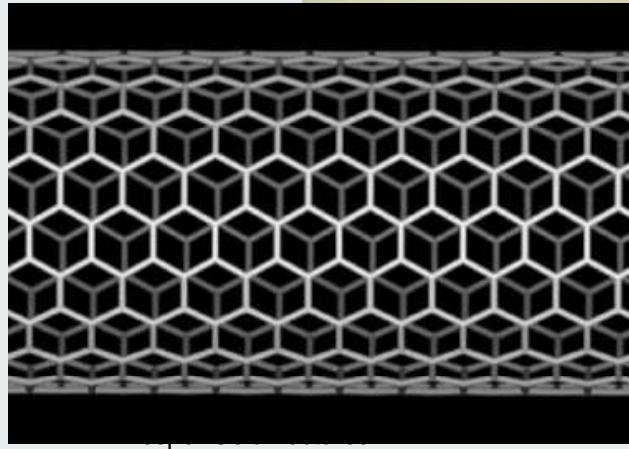
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SWCNTs - Single Wall Carbon Nanotubes

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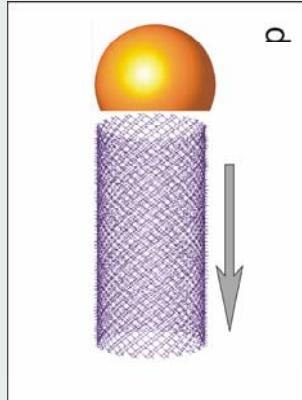
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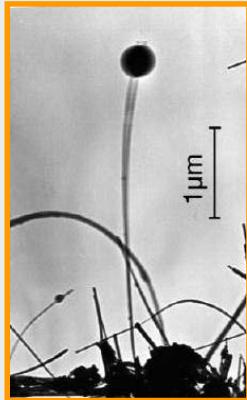
Carbon Nanotubes - Growth

good physical and chemical properties.^[1-3] Various methods for the synthesis of CNTs have been reported: arc-discharge,^[3,4] laser ablation,^[5] chemical vapor deposition,^[6-10] flame synthesis,^[11] and Smalley's recent invention of the high-pressure carbon monoxide (HiPCO) process.^[12] However, none of these methods can be used at low temperature, so the synthesis of CNTs with low-melting point materials, such as organic polymers, has been severely limited. Furthermore, expensive vacuum equipment is necessary to lower the temperature of the synthesis.^[13-16] Therefore, the strategy frequently used has been

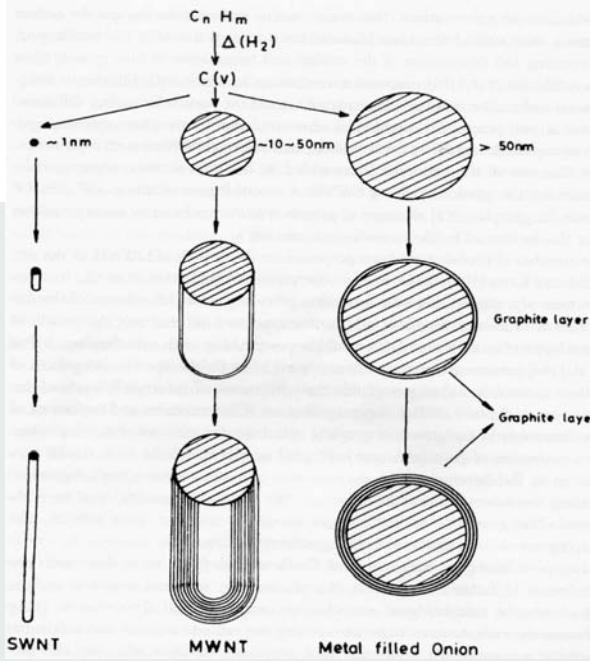
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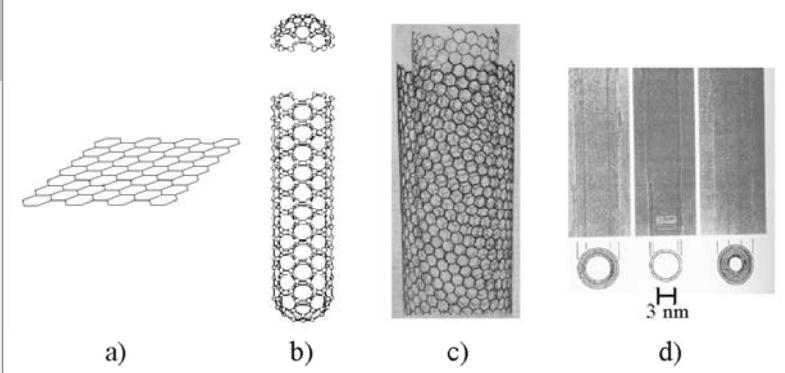
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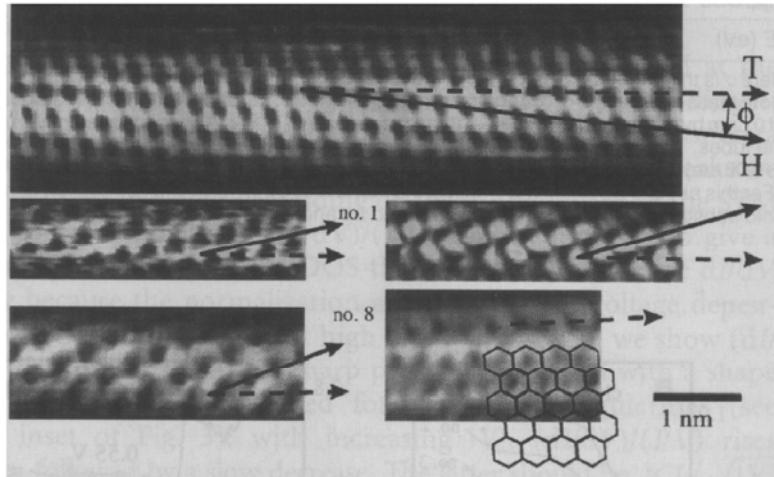
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Carbon Nanotubes - Building Principles

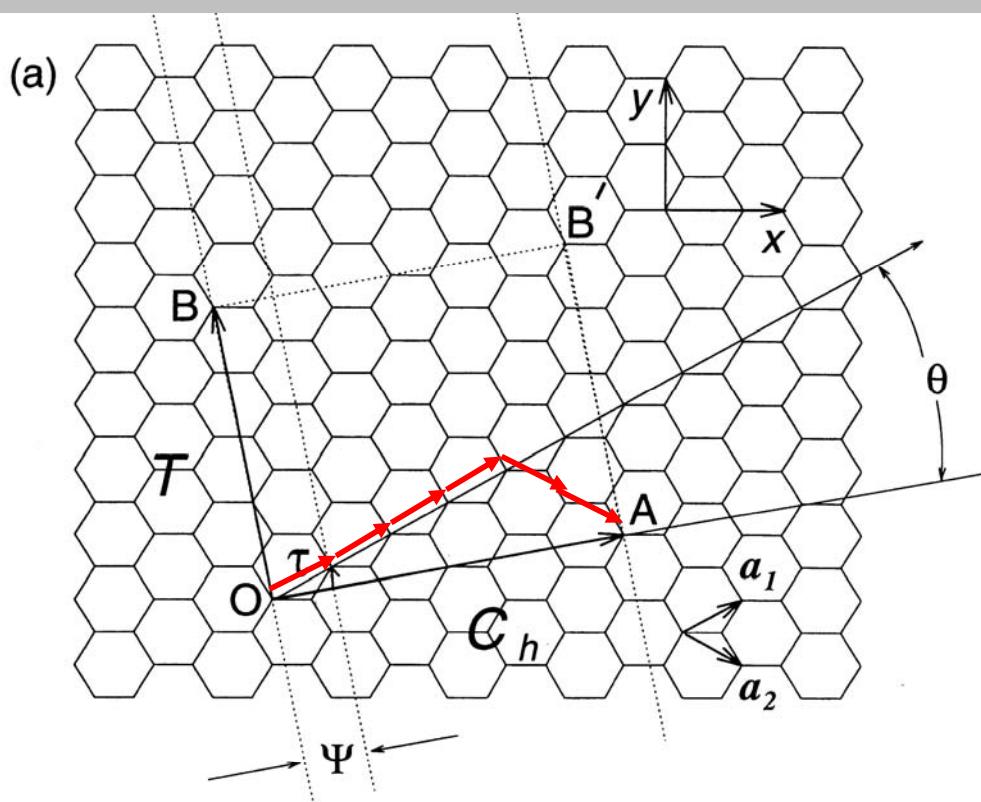
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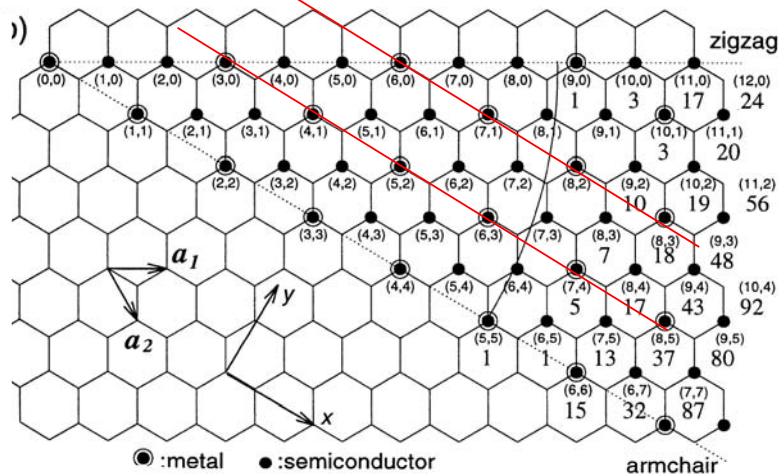
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Carbon Nanotubes - Building Principle



Carbon Nanotubes - Building Principle



19.2. (a) The chiral vector \vec{OA} or $\mathbf{C}_h = n\mathbf{a}_1 + m\mathbf{a}_2$ is defined on the honeycomb lattice of carbon atoms by unit vectors \mathbf{a}_1 and \mathbf{a}_2 and the chiral angle θ with respect to the zigzag axis. Along the zigzag axis, $\theta = 0^\circ$. Also shown are the lattice vector $\mathbf{OB} = \mathbf{T}$ of the tubule unit cell and the rotation angle ψ and the translation τ which constitute the symmetry operation $R = (\psi | \tau)$ for the carbon nanotube. The diagram is constructed for $\mathbf{C}_h = (4, 2)$. (b) Possible vectors specified by the pairs of integers (n, m) for general carbon nanotubes, including zigzag, armchair, and chiral tubules. Below each pair of integers (n, m) is the number of distinct caps that can be joined continuously to the carbon tubule denoted by (n, m) [19.4], as discussed in §19.2.3. The encircled dots denote metallic tubules while the dots are for semiconducting tubules.

Carbon Nanotubes - Building Principle

Diameter of nanotube, $d_t = |C_h| / \pi$

$$\therefore d_t = \frac{a\sqrt{n^2 + m^2 + nm}}{\pi}$$

Let $\mathbf{T} = t_1\mathbf{a}_1 + t_2\mathbf{a}_2$ where t_1 and t_2 are integers

Since \mathbf{T} is perpendicular to \mathbf{C}_h ,

$$t_1 = (2m + n) / d_R \quad \text{and} \quad t_2 = -(2n + m) / d_R$$

d_R is the Greatest Common Divisor (GCD) of $(2m + n)$ and $(2n + m)$,

$d_R = d$ if $(n - m)$ is not a multiple of $3d$

$d_R = 3d$ if $(n - m)$ is a multiple of $3d$

d is the GCD of n and m

Let $\mathbf{T} = t_1\mathbf{a}_1 + t_2\mathbf{a}_2$ where t_1 and t_2 are integers

Since \mathbf{T} is perpendicular to \mathbf{C}_h ,

$$t_1 = (2m + n) / d_R \quad \text{and} \quad t_2 = -(2n + m) / d_R$$

d_R is the Greatest Common Divisor (GCD) of $(2m + n)$ and $(2n + m)$,

$d_R = d$ if $(n - m)$ is not a multiple of $3d$

$d_R = 3d$ if $(n - m)$ is a multiple of $3d$

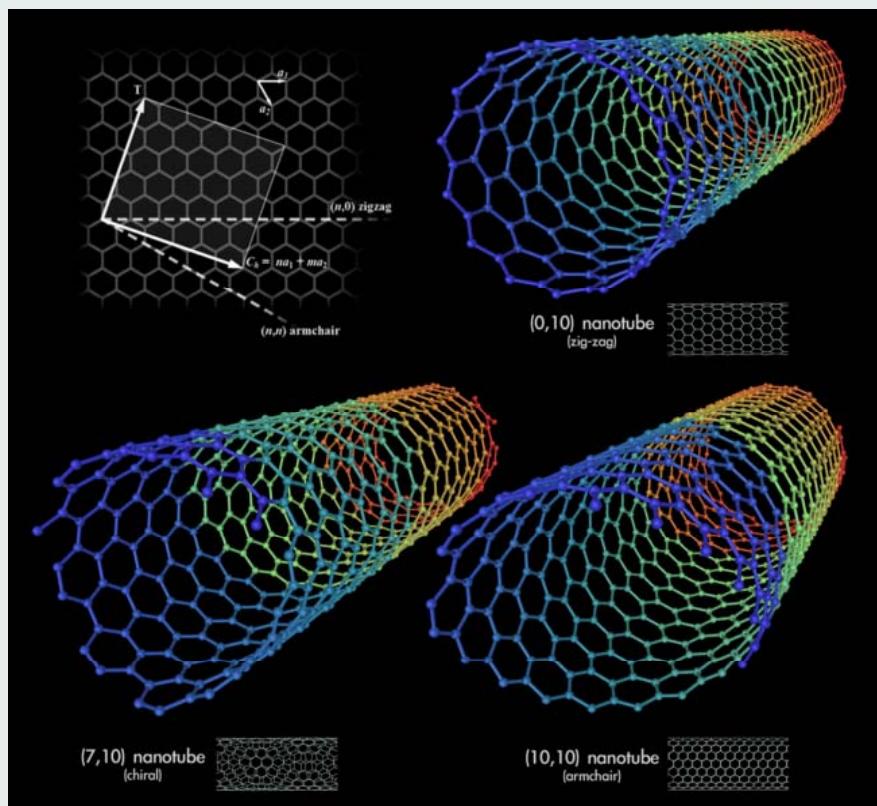
d is the GCD of n and m

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Carbon Nanotubes - Building Principle



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Carbon Nanotubes - Building Principles

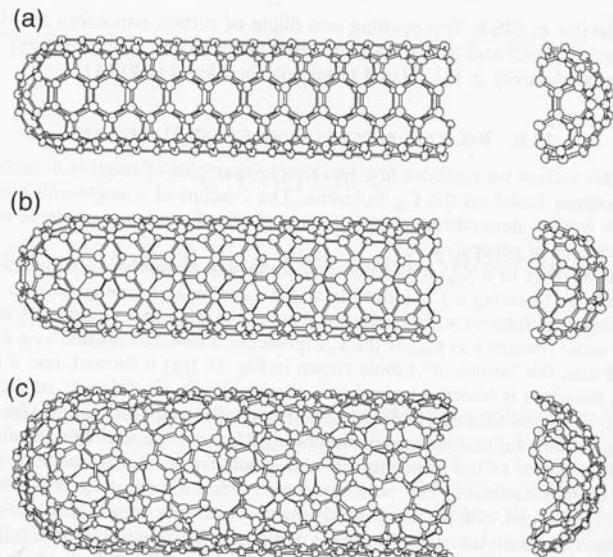


Fig. 19.1. By rolling a graphene sheet (a single layer from a 3D graphite crystal) into a cylinder and capping each end of the cylinder with half of a fullerene molecule, a “fullerene-derived tubule,” one atomic layer in thickness, is formed. Shown here is a schematic theoretical model for a single-wall carbon tubule with the tubule axis normal to: (a) the $\theta = 30^\circ$ direction (an “armchair” tubule), (b) the $\theta = 0^\circ$ direction (a “zigzag” tubule), and (c) a general direction $0 < \theta < 30^\circ$ (see Fig. 19.2) (a “chiral” tubule). The actual tubules shown in the figure correspond to (n, m) values of: (a) $(5, 5)$, (b) $(9, 0)$, and (c) $(10, 5)$ [19.5].

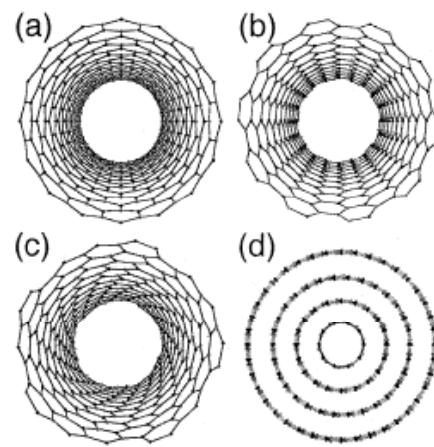


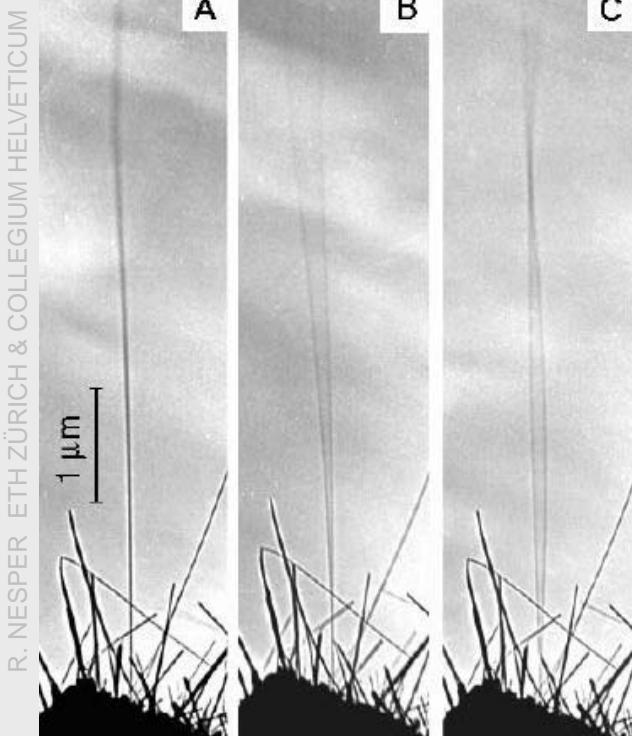
Fig. 1. Models of different nanotube structures. (a)–(c) are SWNTs of 1.25 nm diameter of (a) zig-zag, (b) armchair, and (c) chiral type. (d) represents a MWNT formed by four armchair tubes of increasing diameter with an interlayer separation of 0.34 nm. The image has been reduced by a factor of 2 with respect to images (a)–(c). The images have been generated with the software Mathematica 4.0 using a notebook by Brandbyge [197] that allows one to draw the structure as well as to compute the energy bands of SWNTs.

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Dynamics of C-NTs



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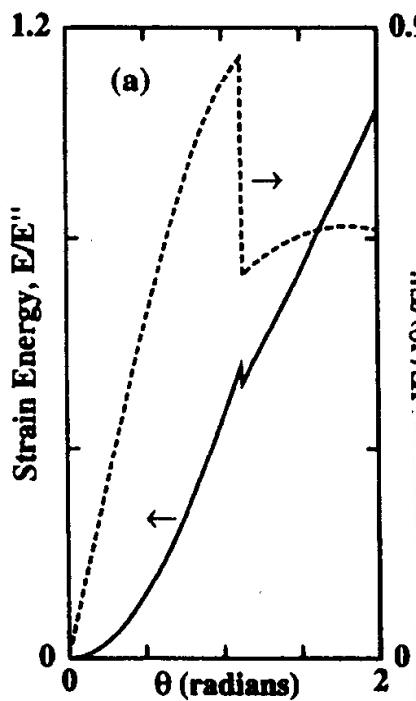


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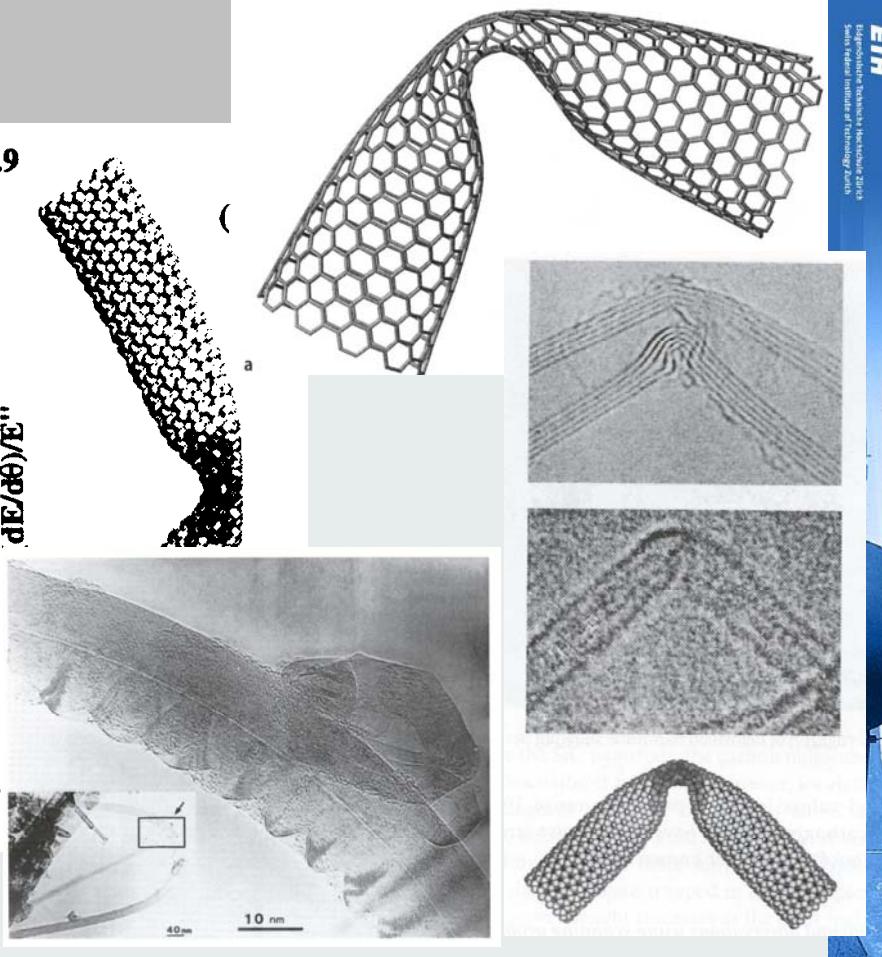
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Strength of CNTs



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Carbon Nanotubes Models

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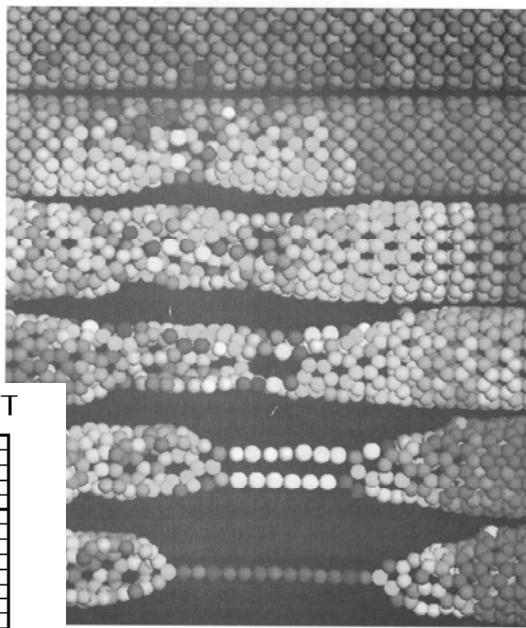
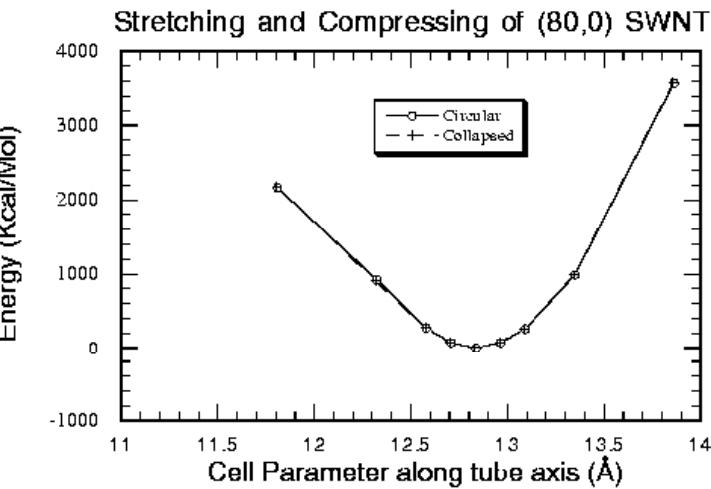
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Strength of CNTs

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SWCNT - Plastic Deformation

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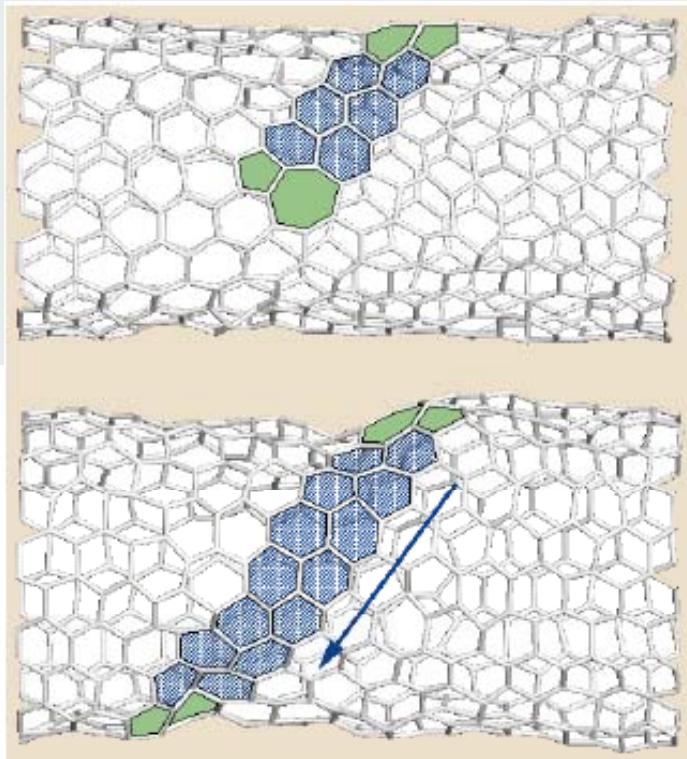


Figure 1 Plastic deformation of a carbon nanotube. Molecular dynamics simulations of a (10,10) nanotube under axial tension (J. Bernholc, M. Buongiorno Nardelli and B. Yakobson). Plastic flow behaviour is shown after 2.5 ns at $T = 3,000$ K and 3% strain. The blue area indicates the migration path (in the direction of the arrow) of the edge dislocation (green). This sort of behaviour might help make composite materials that are really tough (as measured by their ability to absorb energy).

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Carbon Nanotubes

<http://www.pa.msu.edu/cmp/csc/nanotube.html>

Characterization of
each individual
set of nanoparticles
necessary

Density:	1.35 g/cm ³
Resistivity	10 ⁻⁴ wcm
Maximum Current Density	10 ⁹ A/cm ²
Thermal Conductivity	~2000 W/mK
Relaxation Time	~10 ⁻¹¹ s
Elastic Behavior	
Young's Modulus (SWNT)	~1 TPa
Young's Modulus (MWNT)	1.28 TPa
Maximum Tensile Strength	~100 GPa

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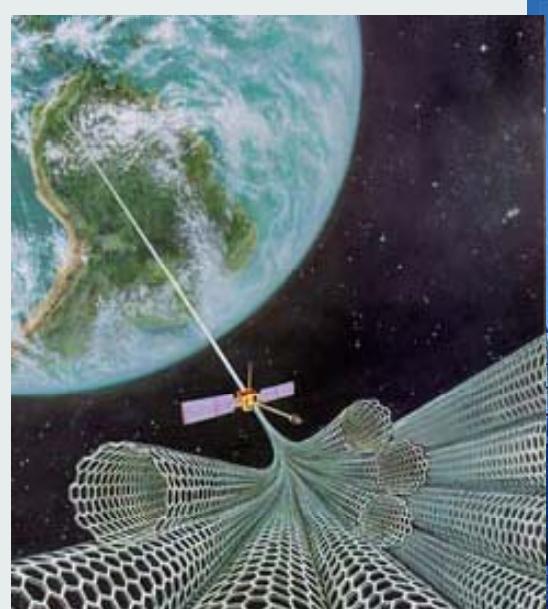
Next Generation Aerospace Material ??

Carbon Nanotube

Nanotube Fiber

Nanotube/ Polymer

Ultra Nanostructured Composite

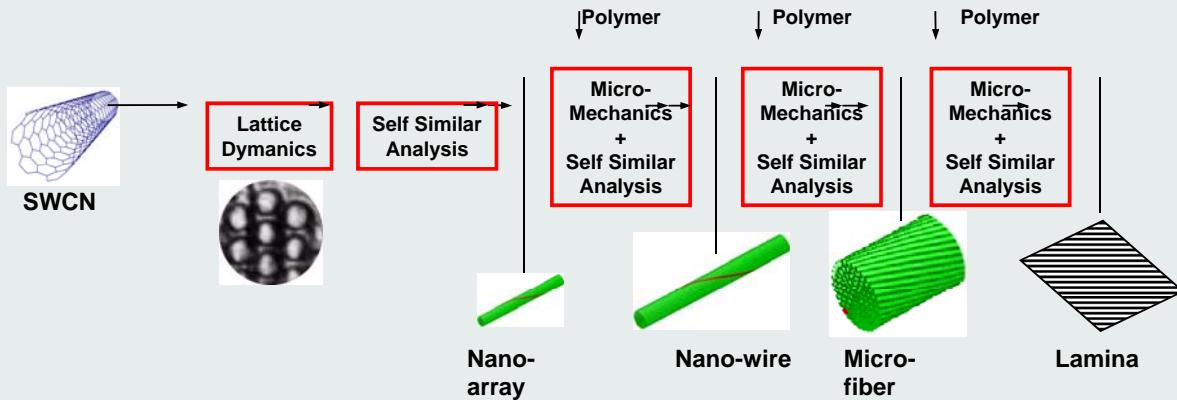


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Self Similar Helical Modeling



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Self-Similar Scales

$1.38 \times 10^{-9} \text{ m}$

SWCN

$1.48 \times 10^{-8} \text{ m}$

SWCN Nano Array

$1.68 \times 10^{-7} \text{ m}$

SWCN Nano Wire

$1.92 \times 10^{-6} \text{ m}$

SWCN Micro
Fiber

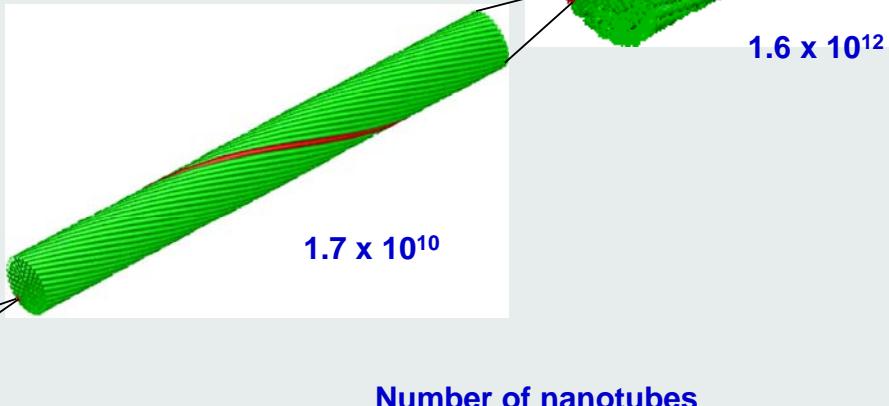
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Self-Similar Scales

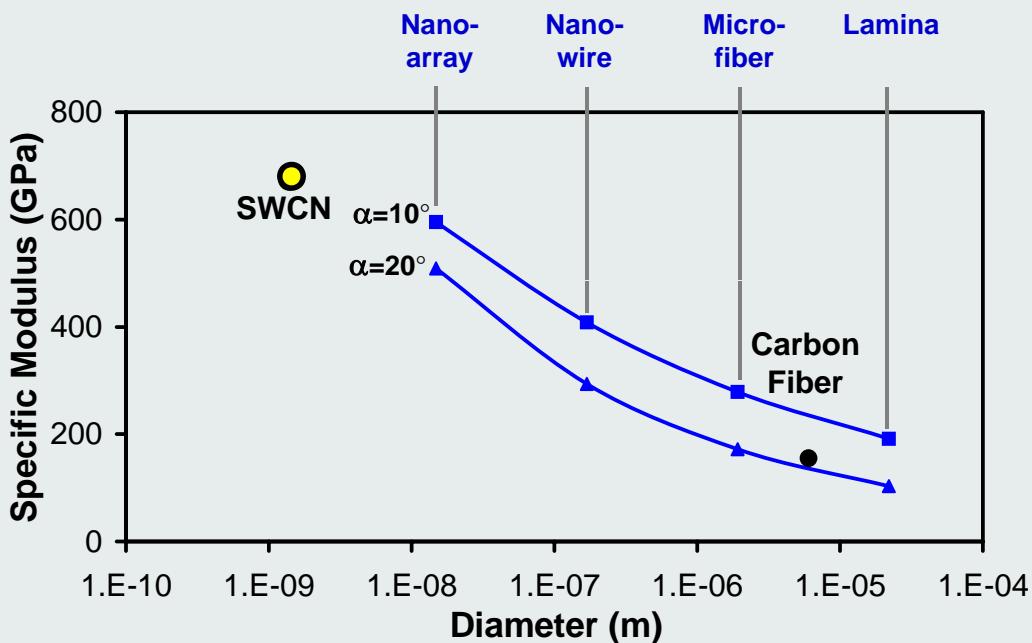
Diameter = 1.92×10^{-6} m
Length = 1.0×10^{-3} m



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Self-Similar Properties

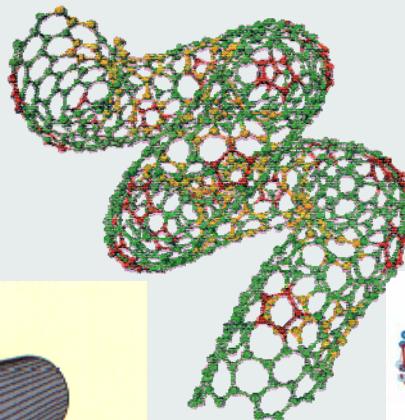
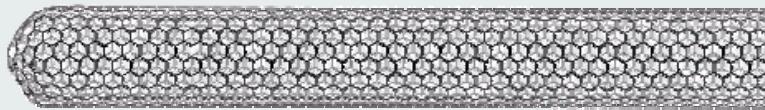


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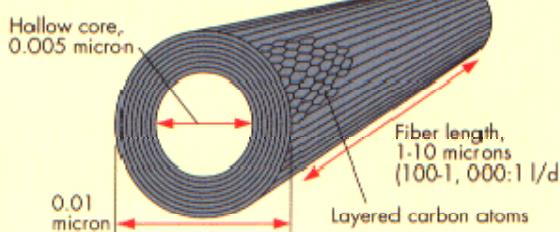
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C-Nanotubes - Forms

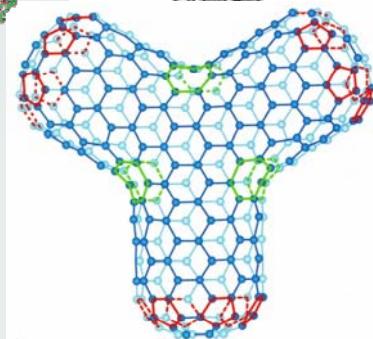
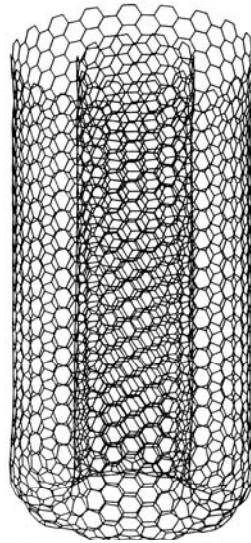


**Rolled-up graphite sheets
(typically eight layers)**

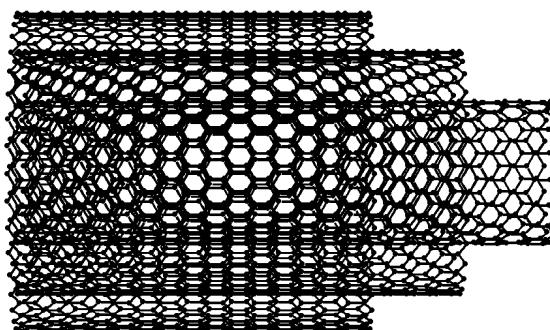
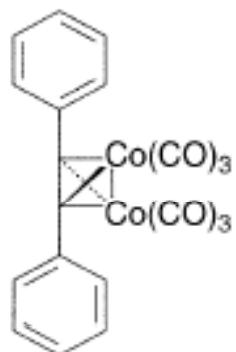


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D ~ 0.34 nm

Multiwalled Carbon Nanotubes

Synthesis below 500 °C

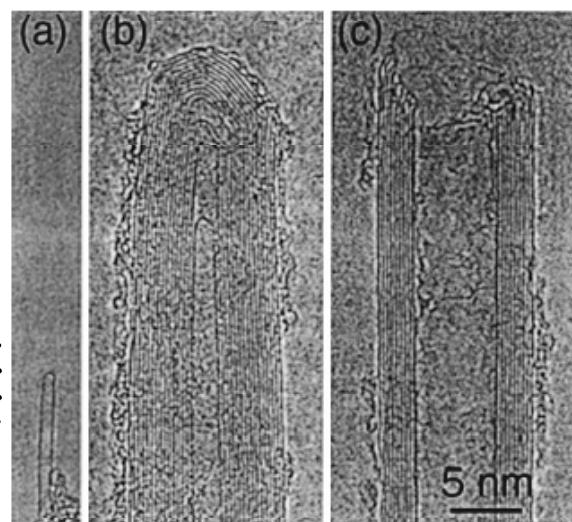


Fig. 2. TEM pictures of the ends of (a) a SWNT, (b) a closed MWNT, and (c) an open MWNT. Each black line corresponds to one graphene sheet viewed edge-on. The micrographs are reproduced at the same magnification.

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C-Nanotubes - Multiwall Connections

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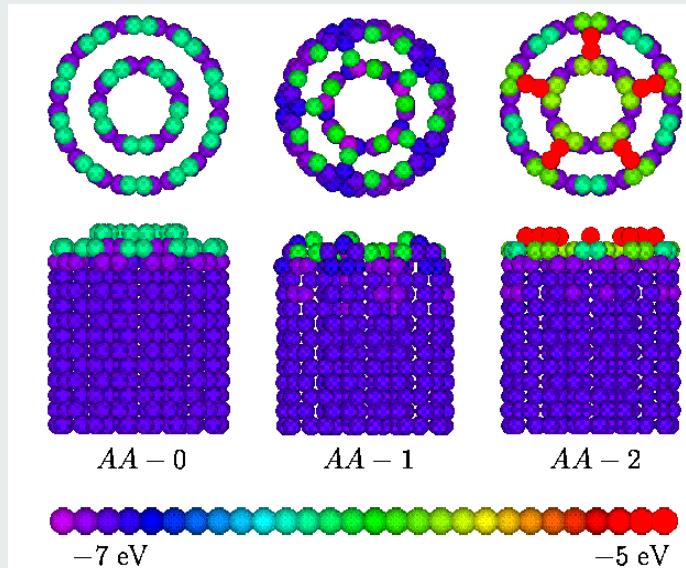
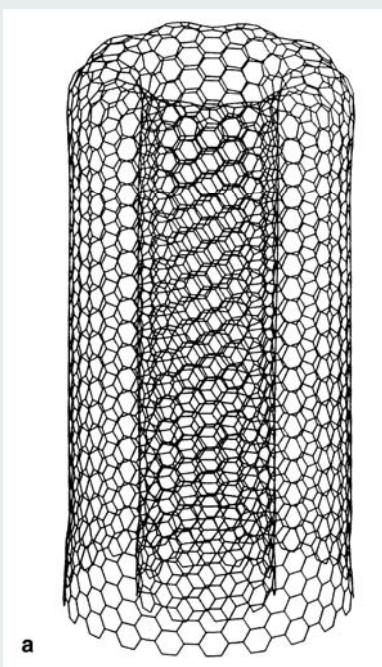


Figure 2

(Young-Kyun Kwon et al., "Morphology and stability of growing multi-wall carbon nanotubes")

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Helices, Springs, Actuators

VETICUM



Abb. 6. a) Rasterelektronenmikroskopische (REM)-Aufnahme mehrerer pyrolytisch synthetisierter spiral-förmiger Nanoröhrchen. b) Theoretisches Modell der korkenzieherartigen Gebilde.

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Other new CNTs ?

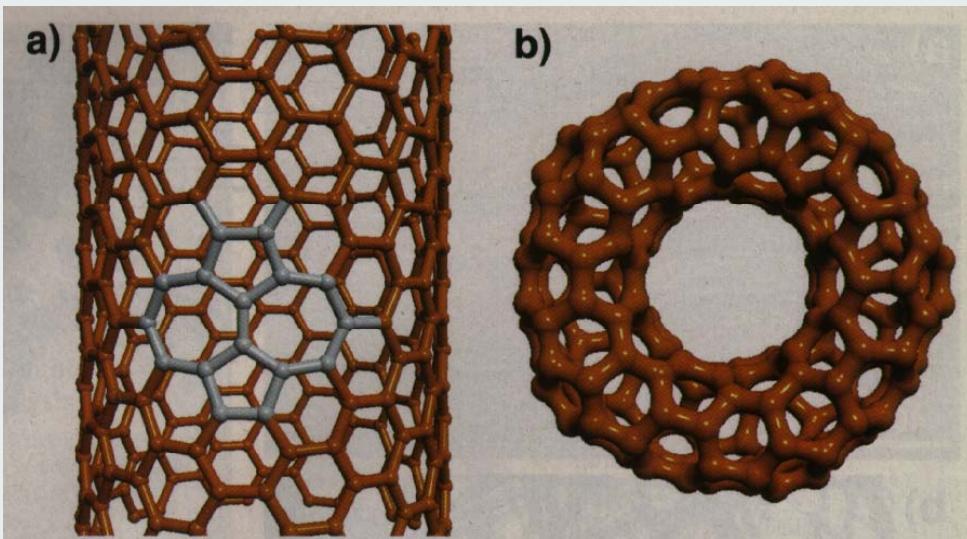


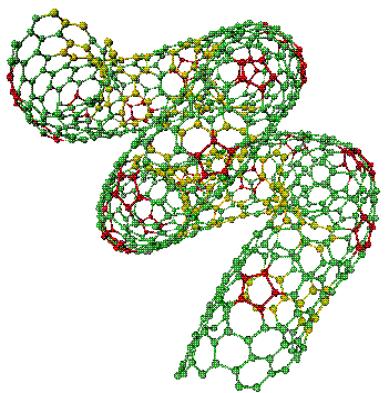
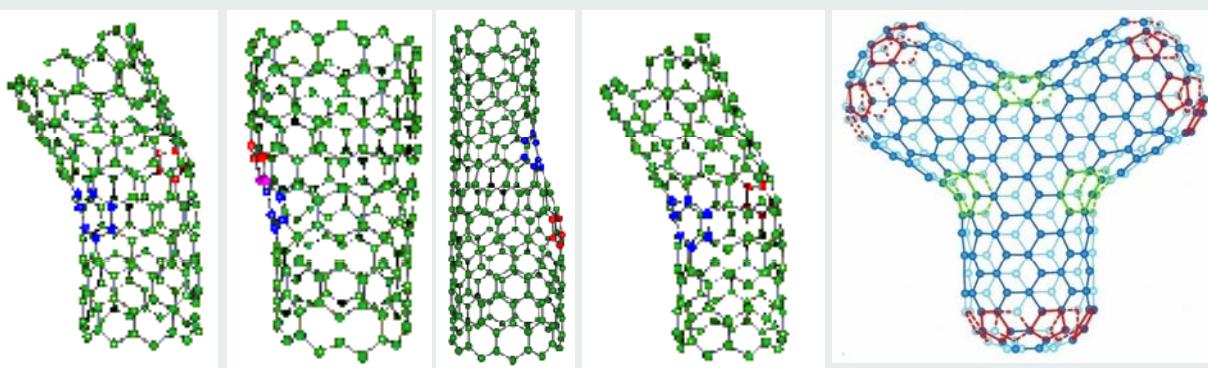
Abb. 5. a) Modell eines einwandigen Kohlenstoff-Nanoröhrchens mit einem 5,7-Defekt, der aus vier Sechsecken über eine Stone-Wales-Transformation entsteht. b) Durch den Einbau von Fünf- und Siebenekken an bestimmten Stellen entsteht ein ringförmiges Nanoröhrchen; hier schematisch dargestellt. (Bild: Dr. H. Terrones/University of Sussex, U.K.)

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Building Faults, Properties, Electronics

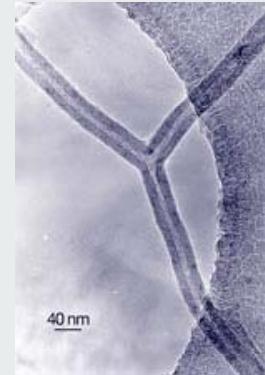


5+7 ring => Diode

But contact resistance !!

Semicond. / metallic CNT
transistor

But no control on helicity!!



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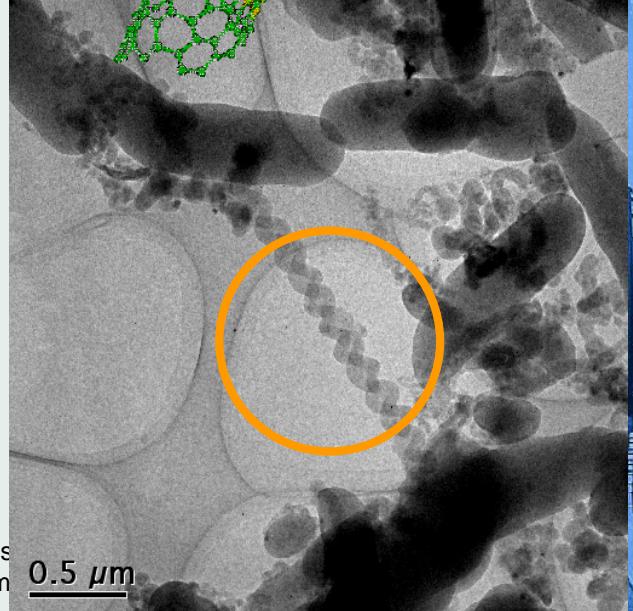
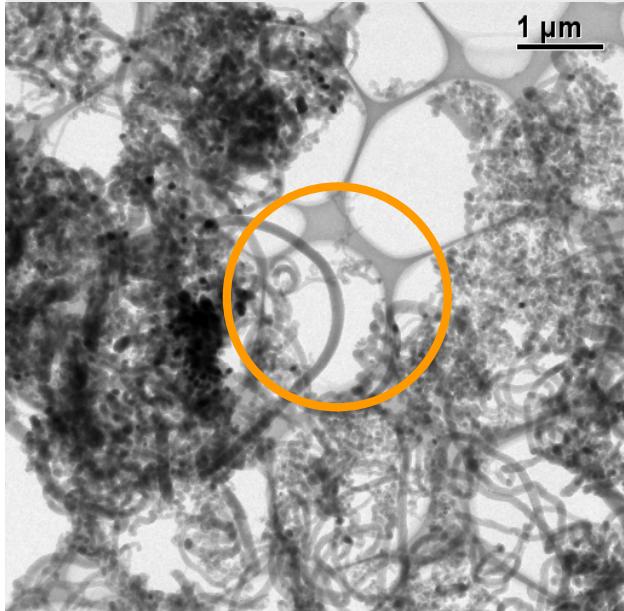
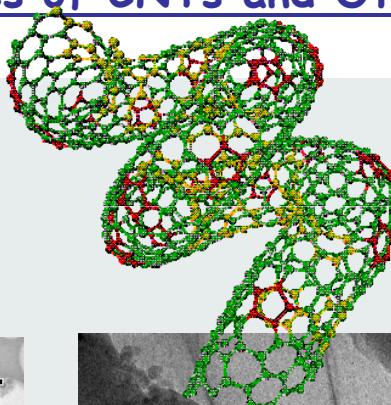
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Low Temperature Syntheses of CNTs and Other C Nanoparticles

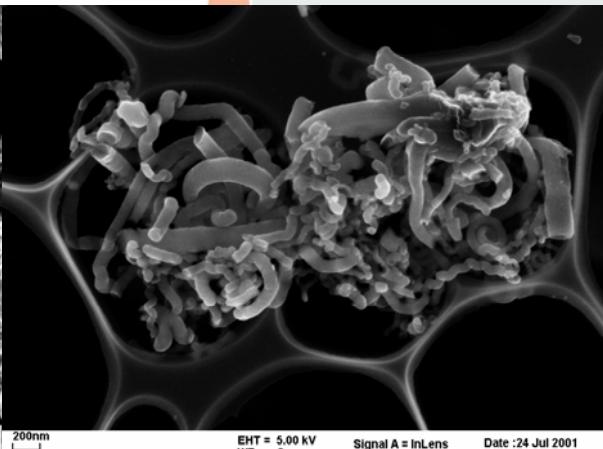
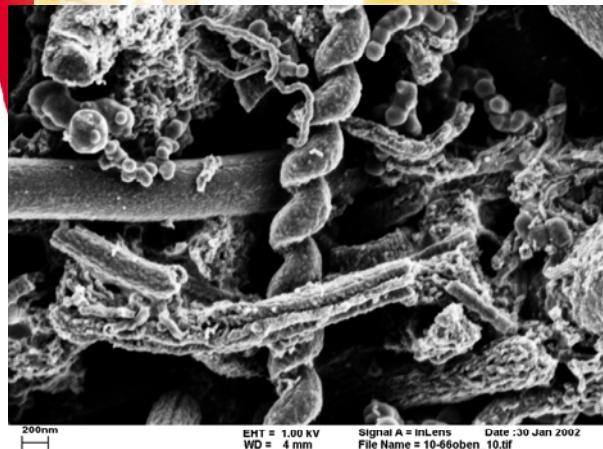
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T < 500 C



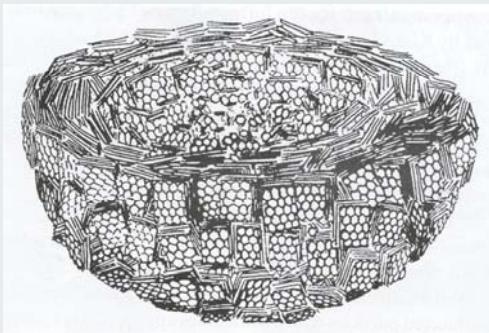
Carbons – All Pasta and Infinite Set ?

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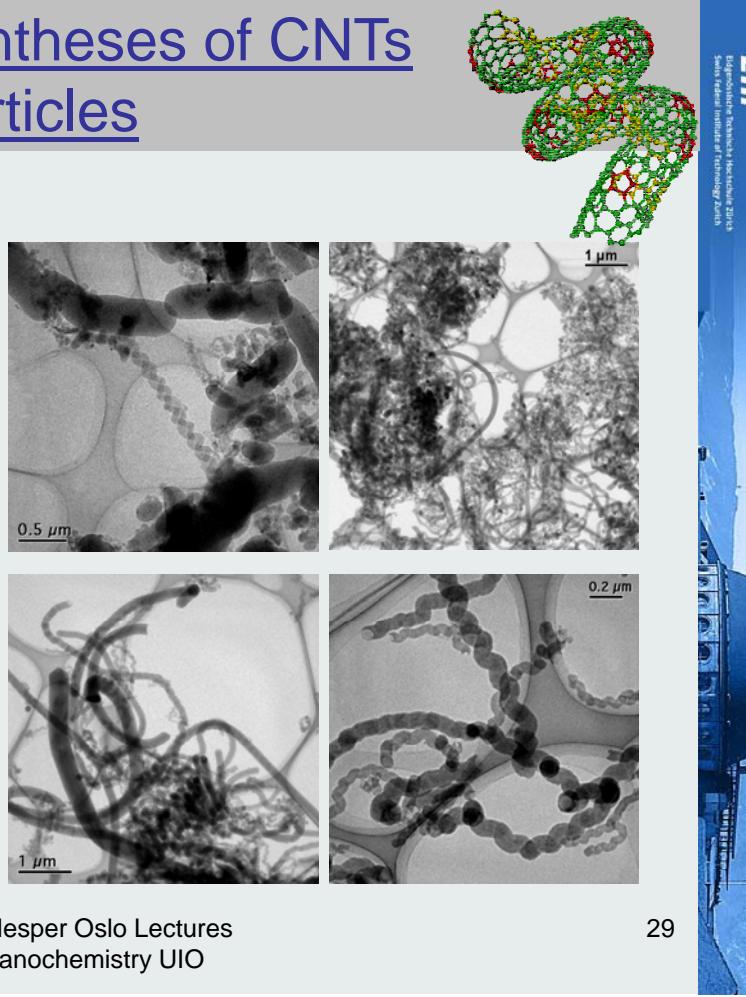


Low Temperature Syntheses of CNTs and Other C Nanoparticles

Fish bone structures



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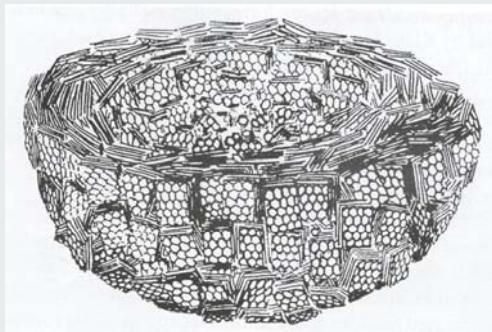


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Low Temperature Syntheses of CNTs

Fish bone structures



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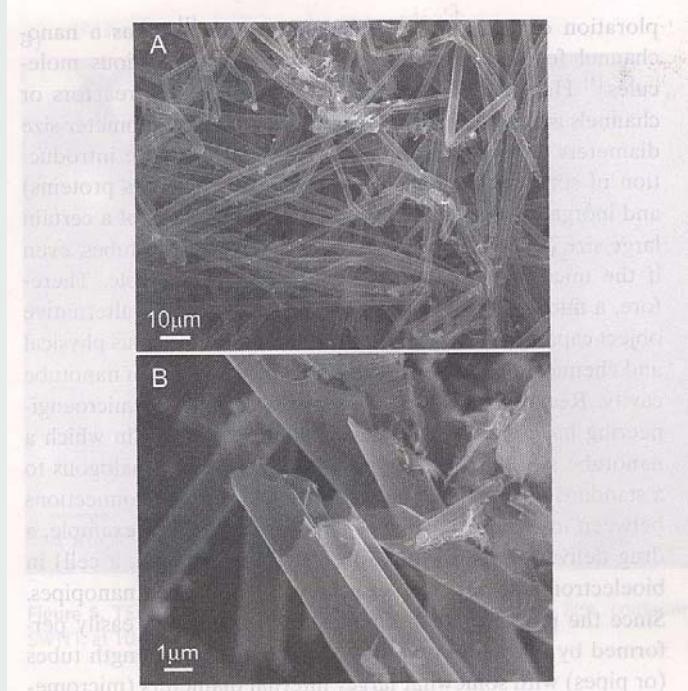


Figure 1. A) Low-magnification SEM image of the carbon microtubes.
B) High-magnification SEM image displaying the open ends of the microtubes.

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Cones, Bamboos etc.

A. Ivantchenko, R. Nesper

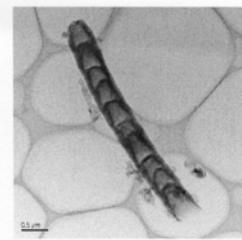
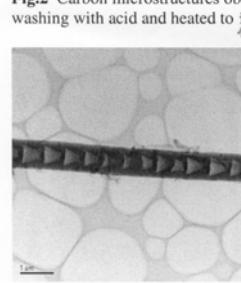
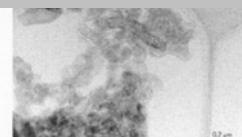
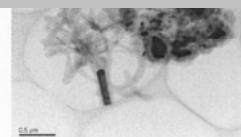
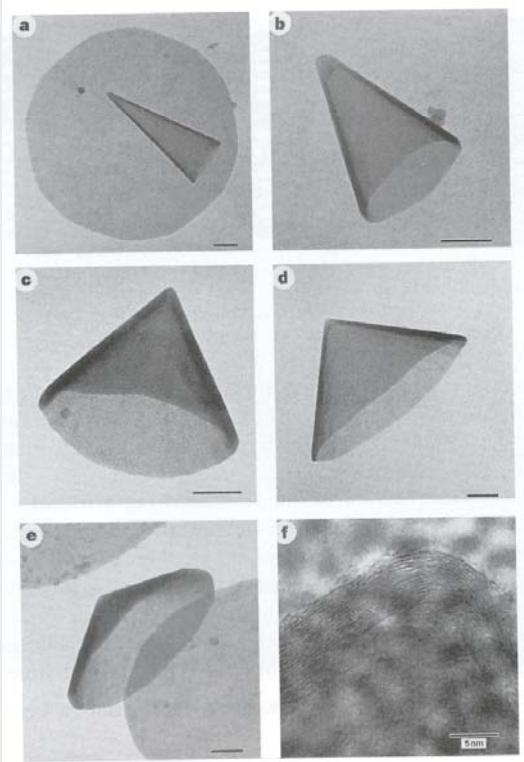


Fig.2 Carbon microstructures obtained (1)after washing with 65% nitric acid (2)after washing with acid and heated to 1000°C in Ar atmosphere
1400

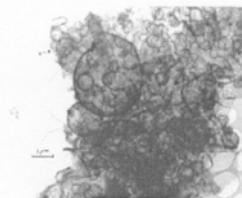
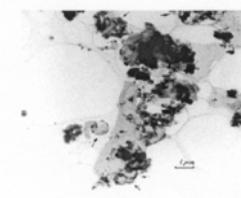


Fig.3 Carbon microstructures obtained (1)after washing with 65% nitric acid (2)after washing with acid and heated to 1000°C in Ar atmosphere
1400

Fig.4 Carbon microstructures obtained (1)after washing with water (2)after washing with concentrated acid

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Storage in CNTs

In a recent work of Baker and Rodriguez [1] indicate a very large specific hydrogen storage capacity in carbon nanotubes (CNT's) and in herringbone materials. Yet, these results have not been confirmed by any research group in the world [1,2,3,6,7,8], but nevertheless they gave rise to enhanced activity in the field of carbon-based hydrogen storage on the theoretical and on the experimental side.

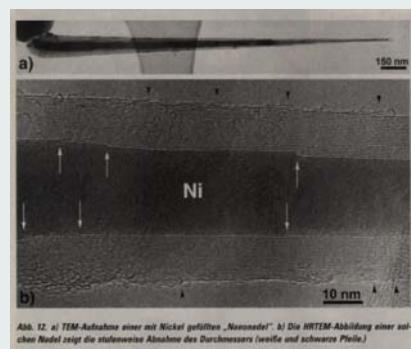
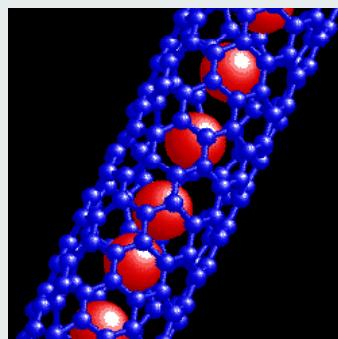


Abb. 12. a) TEM-Aufnahme einer mit Nickel gefüllten „Nanotube“; b) Die HRTEM-Aufnahme einer solchen Nanotube zeigt die stufenweise Absorption des Durchmessers (weiße und schwarze Pfeile.)



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H₂ - Storage in C-NTs ?

wrong !! →

Baker, N. Rodriguez et al., J.Phys.Chem. B 102, 423 (1998)

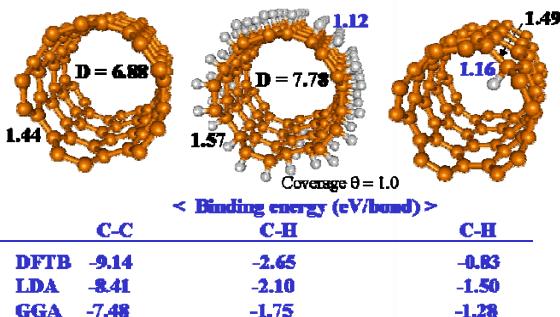
Baker & Rodriguez

65wt% !!???

M. Parrinello

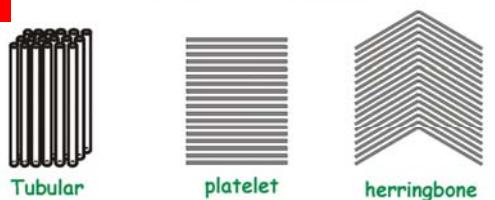
max. 14wt%

Hydrogen adsorption on (5,5) SWNT

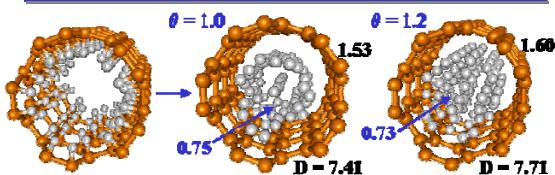


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Hydrogen storage in (5,5) SWNT



Nanotubes Research Lab

Catalyst Patterning for Growth of CNTs

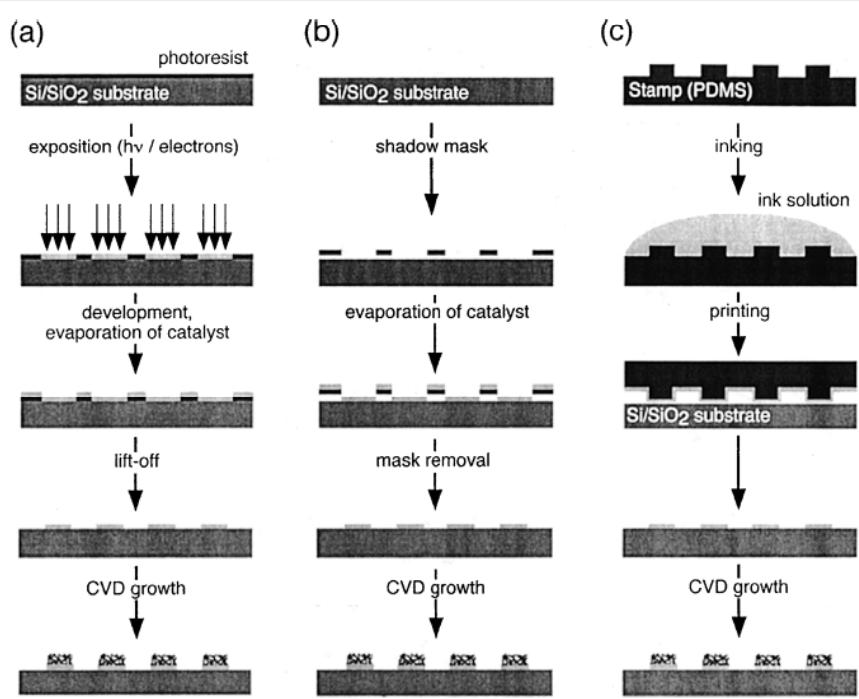


Fig. 4. Techniques to produce patterns of catalysts for the selective growth of carbon nanotubes: (a) standard lithography, (b) shadow-masking, (c) soft lithography.

Hierarchical Order – Aggregations

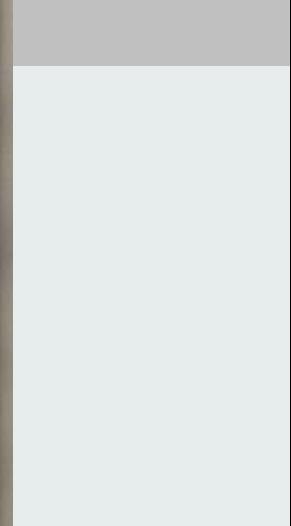
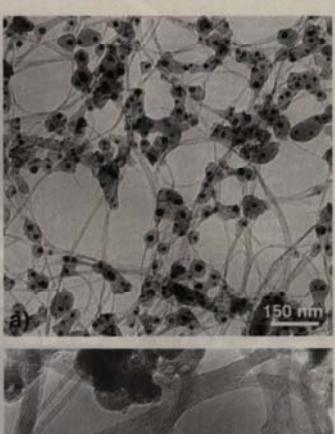
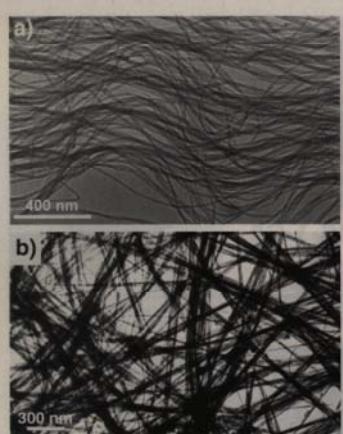


Abb. 8. a) TEM-Übersichtsaufnahme von SWNTs, die im Lichtbogen und dem Einsatz von Metallkatalysatoren synthetisiert werden. b) Großaufnahme der in a) gezeigten SWNT-Bündel.

Abb. 9. a) REM-Aufnahme eines MWNT-Bündels, das während der Pyrolyse organischer Feststoffe gewachsen ist. b) Großaufnahme der ausgerichteten MWNTs dieses Bündels.

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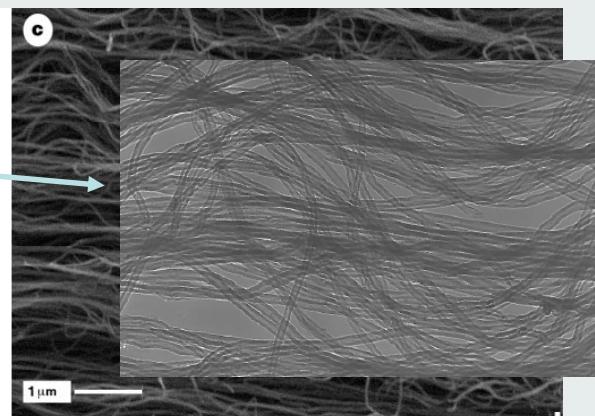
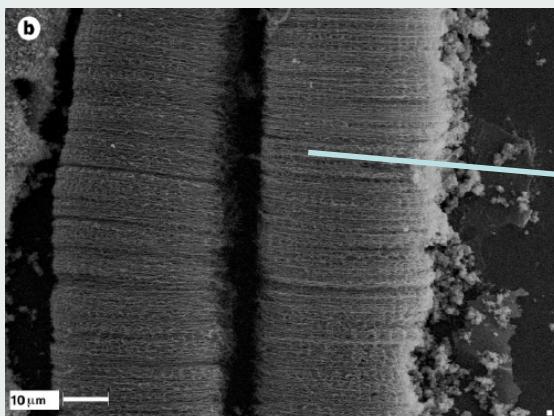
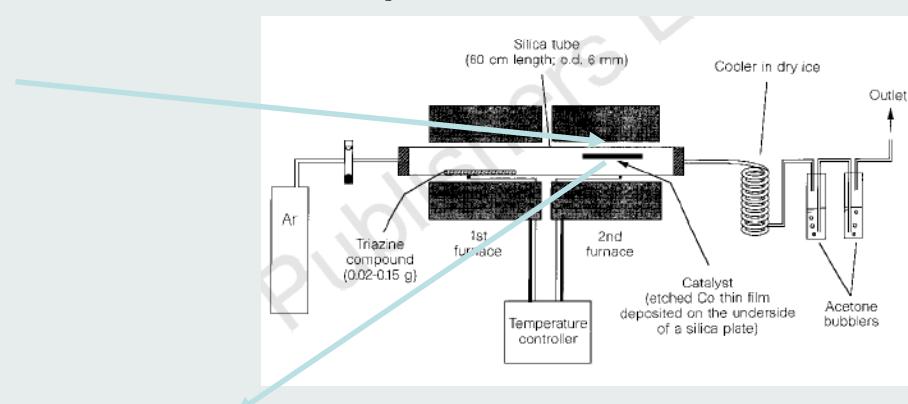
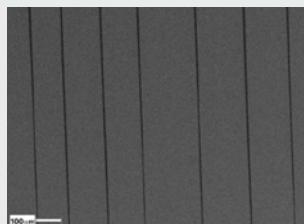


Abb. 10. a) REM-Aufnahme eines MWNT-Bündels, das während der Pyrolyse organischer Feststoffe gewachsen ist. b) Großaufnahme der ausgerichteten MWNTs dieses Bündels.

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Hierarchical Order – Carpets Predefined



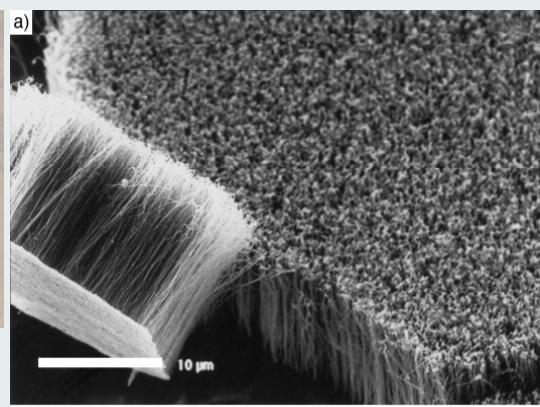
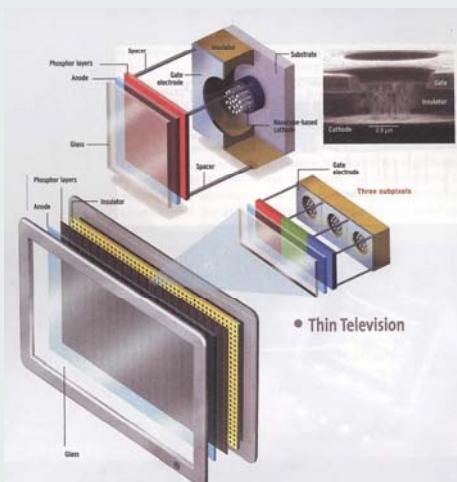
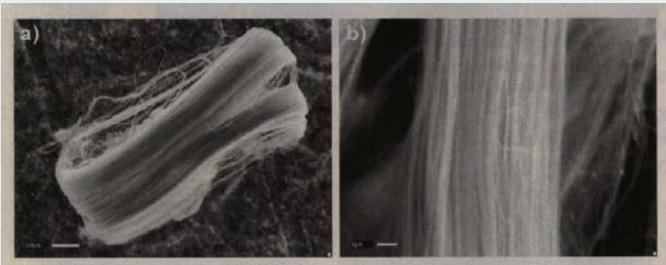
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Hierarchical Order – Carpets etc.

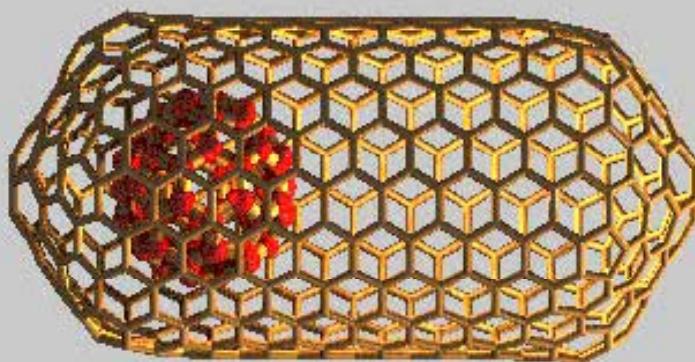


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Fullerene Nanotube Switch

(<http://www.pa.msu.edu/cmp/csc/nanotube.html>)



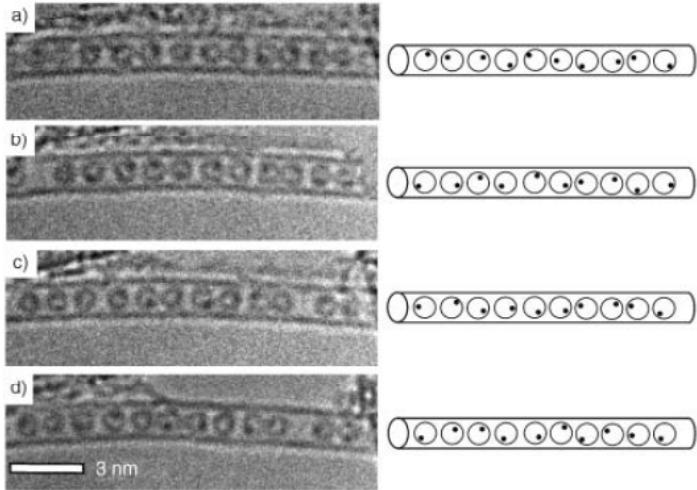
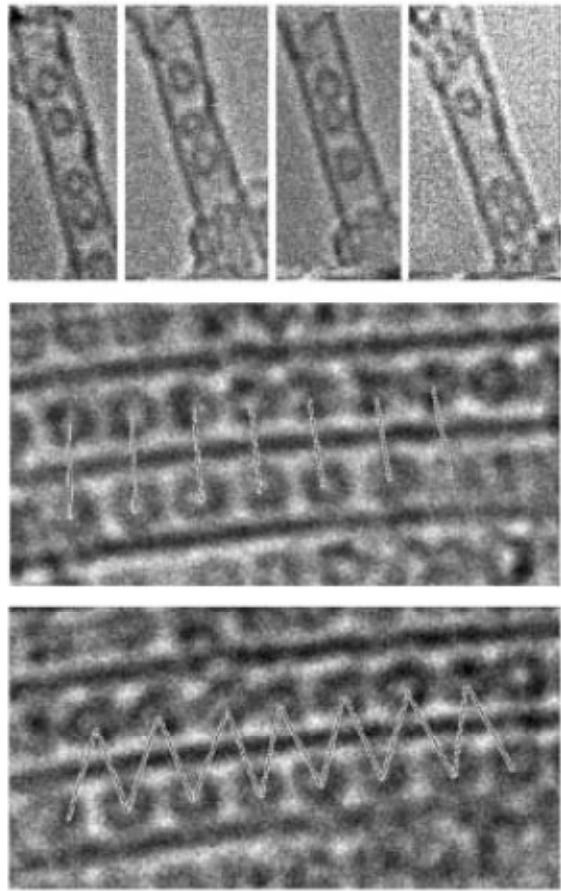
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Filling of Carbon Nanotubes

(Ce@C₈₂)@SWNTs



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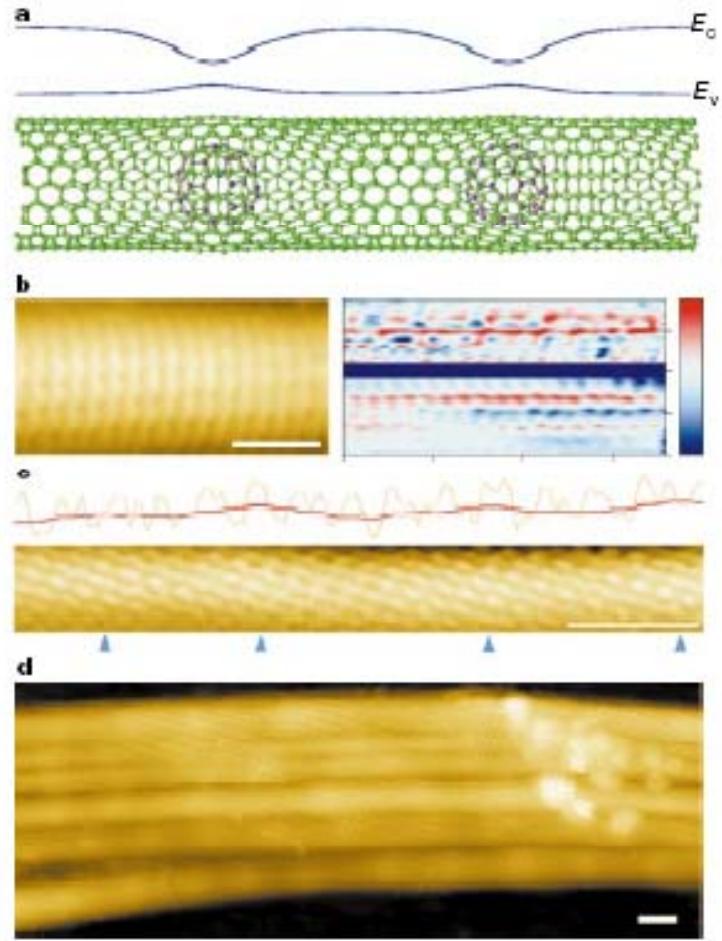
Valence & conduction bands

Elastic strain

STM topography

Atomic resolution

SWT bundle



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N

Applications of CNTs - Thermocouple

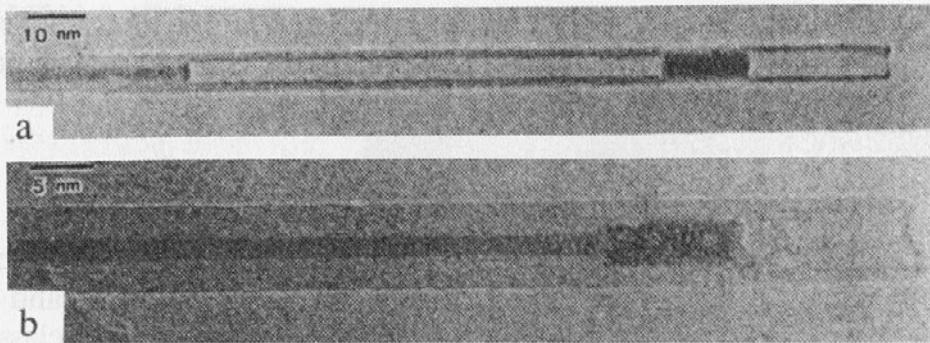


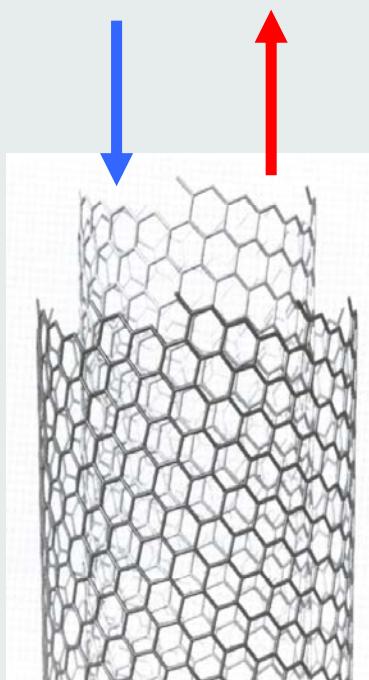
Fig. 19.60. TEM image of nested carbon nanotubes containing a Pb filled core [19.66].

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Tube-in-Tube

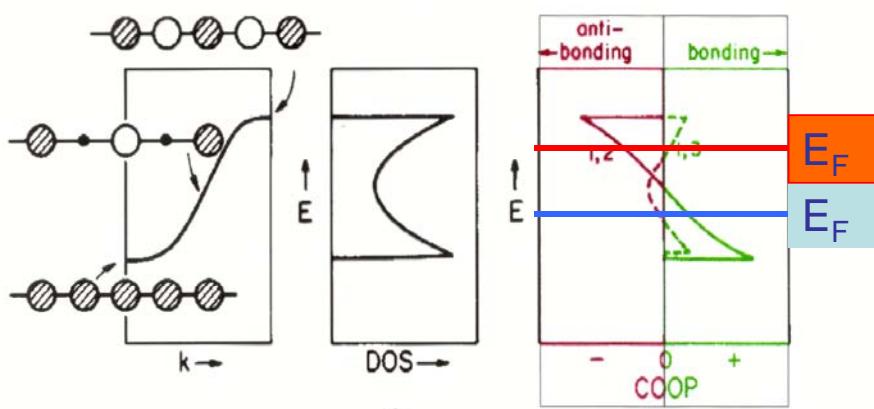
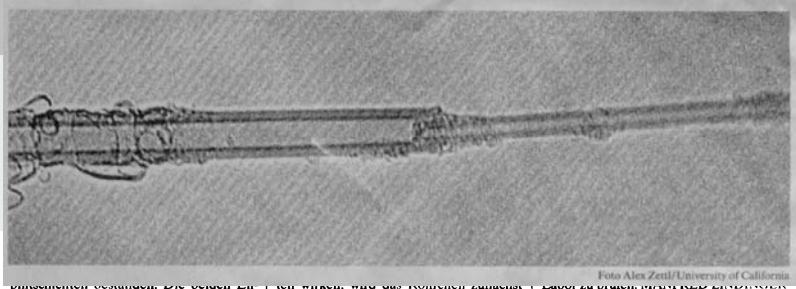


Flinkes Nanoröhrchen schwingt wie winziges Federpendel

Nanoröhrchen aus Kohlenstoff gewinnen wegen ihrer ungewöhnlichen Eigenschaften für die Wissenschaft zunehmend an Bedeutung. Einerseits sind die zylindri-

den der Röhrchen waren zunächst durch mehrlagige Kappen abgeschlossen. Zettl und seine Kollegen entfernen die Kappe an einem Ende und ergriffen die innen-

wieder in das Innere der Graphithülle zurückgezogen. Dort besitzt es aber genügend kinetische Energie, am anderen Ende wieder herauszuschießen. Hat sich



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Field Emission Displays

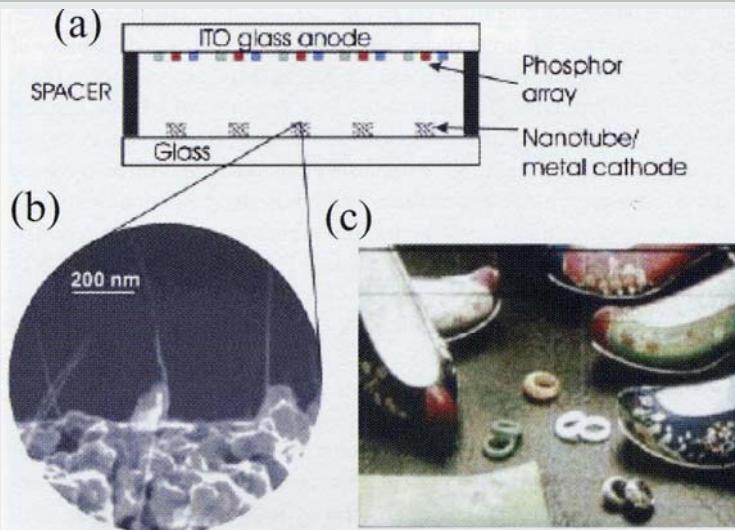
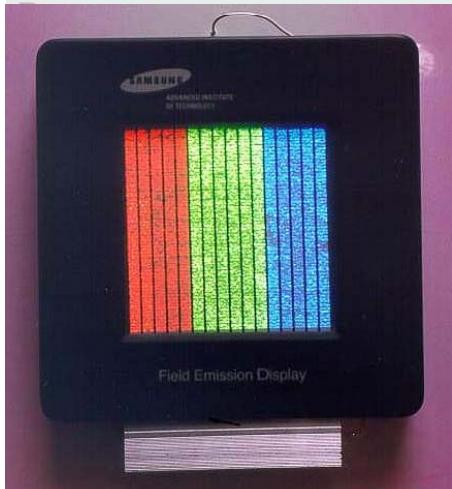


Fig. 8.14. (a) Schematic illustration of a flat panel display based on carbon nanotubes. ITO, indium tin oxide. (b) SEM image of an electron emitter for a display, showing well-separated SWNT bundles protruding from the supporting

metal base. (c) Photograph of a 5 in (13 cm) nanotube field emission display made by Samsung. Reproduced from ref. [187], with permission.

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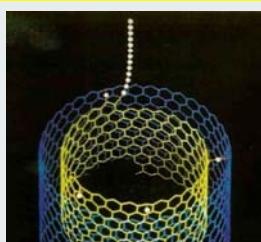
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(C)NT-Applications

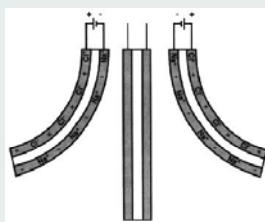
emission tip



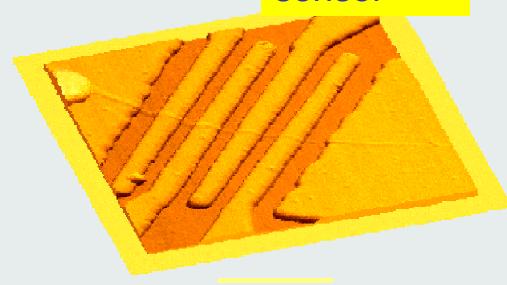
Rinzler, et al., Science, September, 1995

??

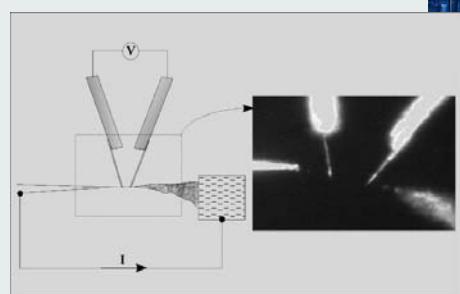
ion sensor
actuator



Conductor
rectifier
transistor
sensor



nano tips



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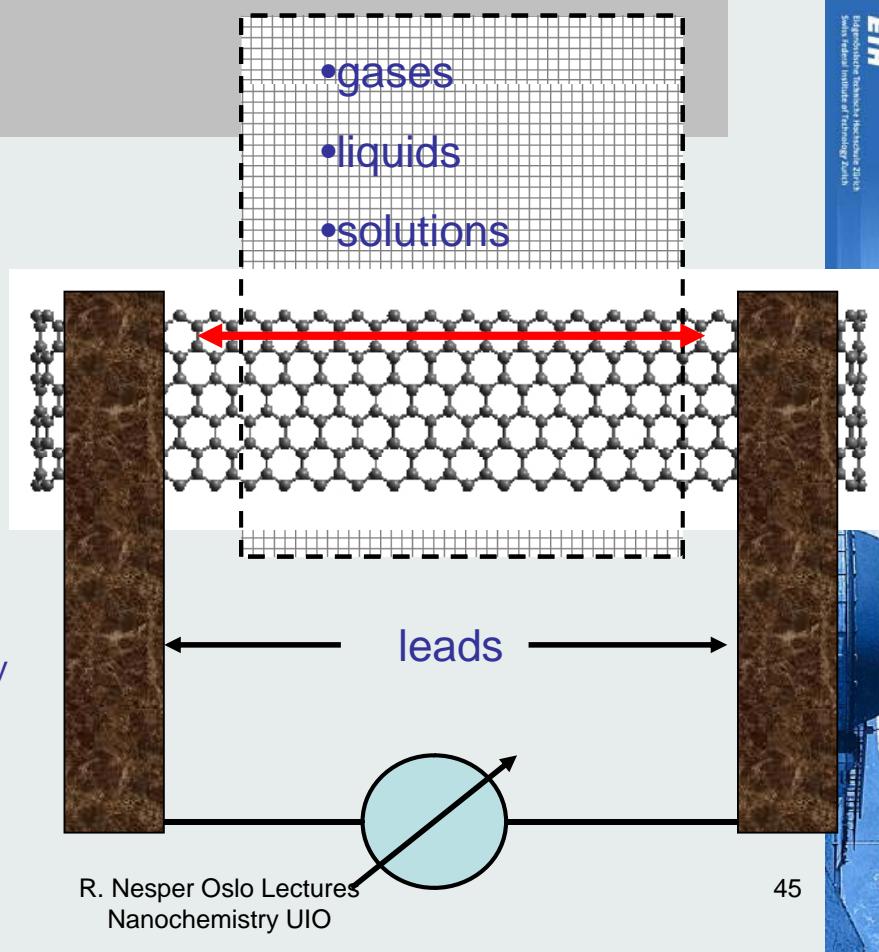
C-NT Sensor

Surface electron conductance

Adsorbed species

strongly change conductivity

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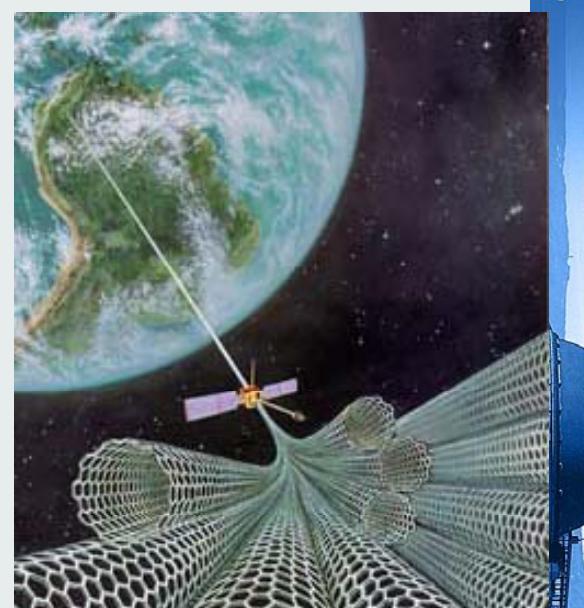
**Next Generation Aerospace Material**

Carbon Nanotube

Nanotube Fiber

Nanotube/ Polymer

Ultra Nanostructured Composite

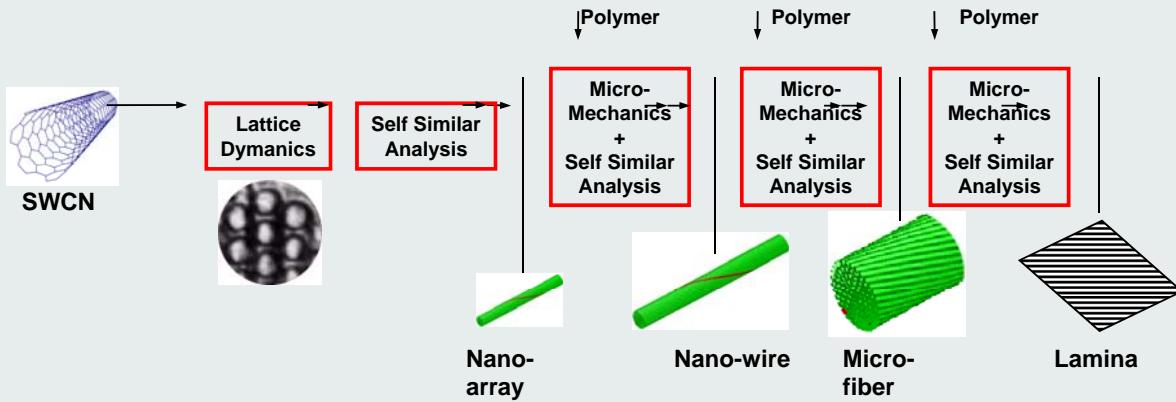


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Self Similar Helical Modeling



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Self-Similar Scales

$1.38 \times 10^{-9} \text{ m}$

SWCN

$1.48 \times 10^{-8} \text{ m}$

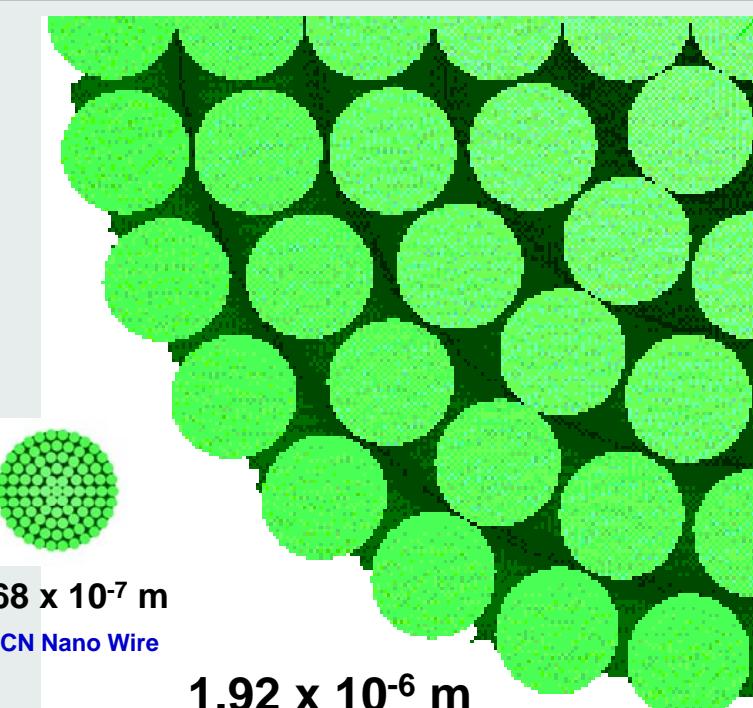
SWCN Nano Array

$1.68 \times 10^{-7} \text{ m}$

SWCN Nano Wire

$1.92 \times 10^{-6} \text{ m}$

SWCN Micro Fiber



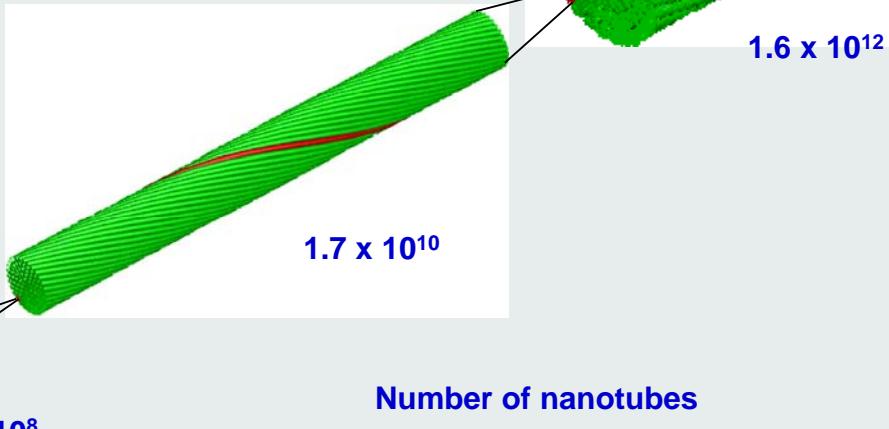
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Self-Similar Scales

Diameter = 1.92×10^{-6} m
Length = 1.0×10^{-3} m

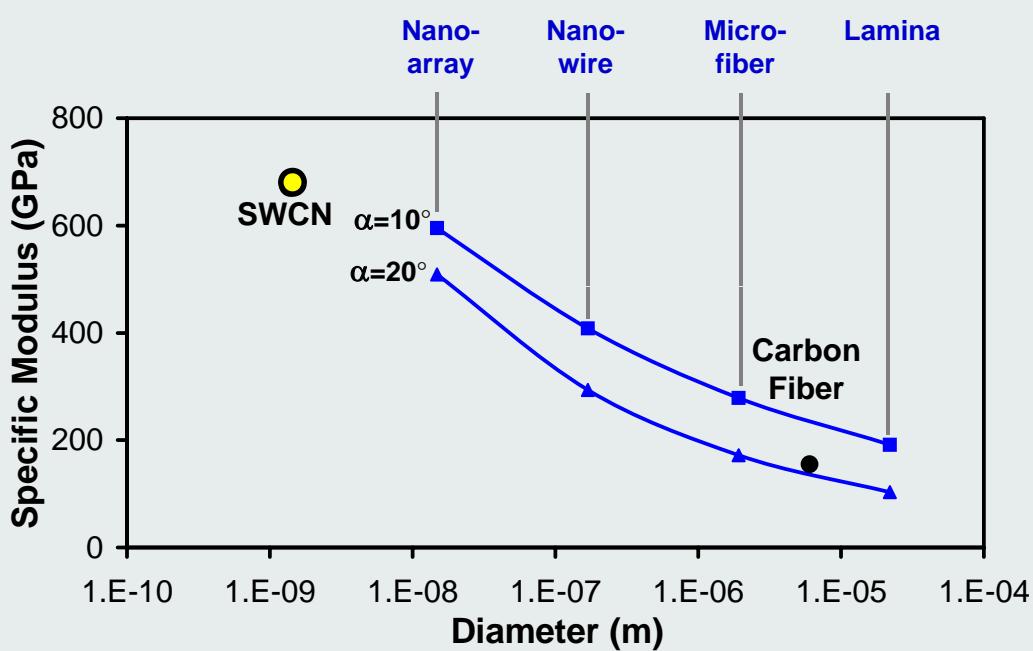


SWCN 10.2008

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Self-Similar Properties

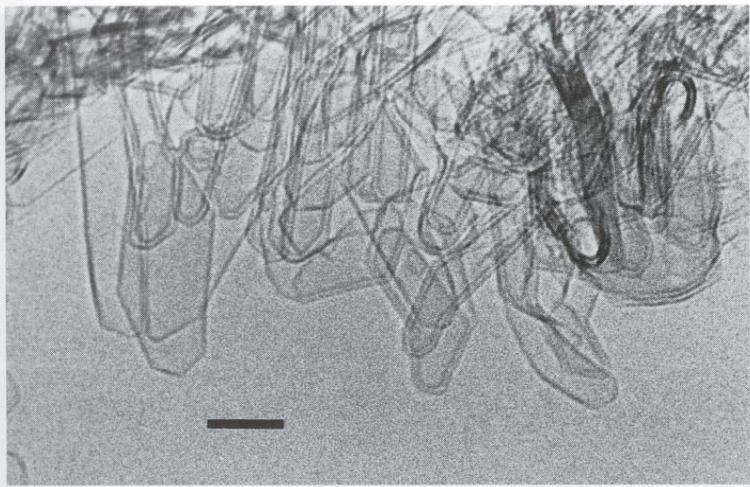
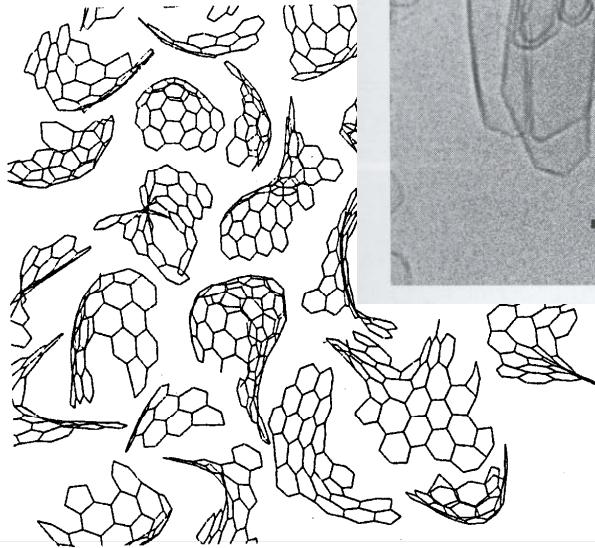


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New Carbons ?



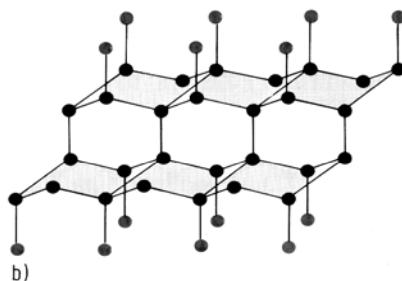
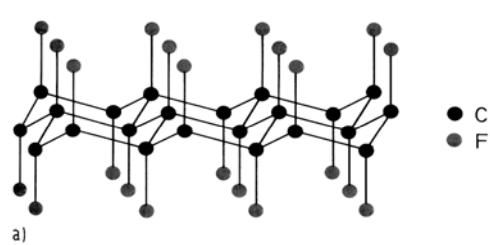
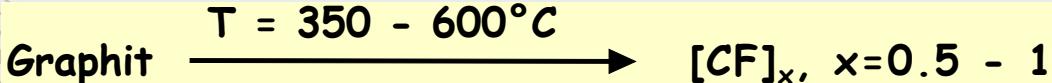
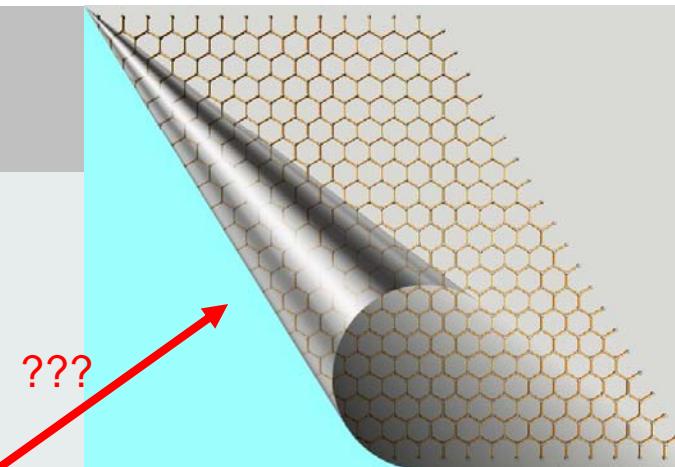
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Derivates of Graphite



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Exfoliate Graphite Intercalation Compounds?

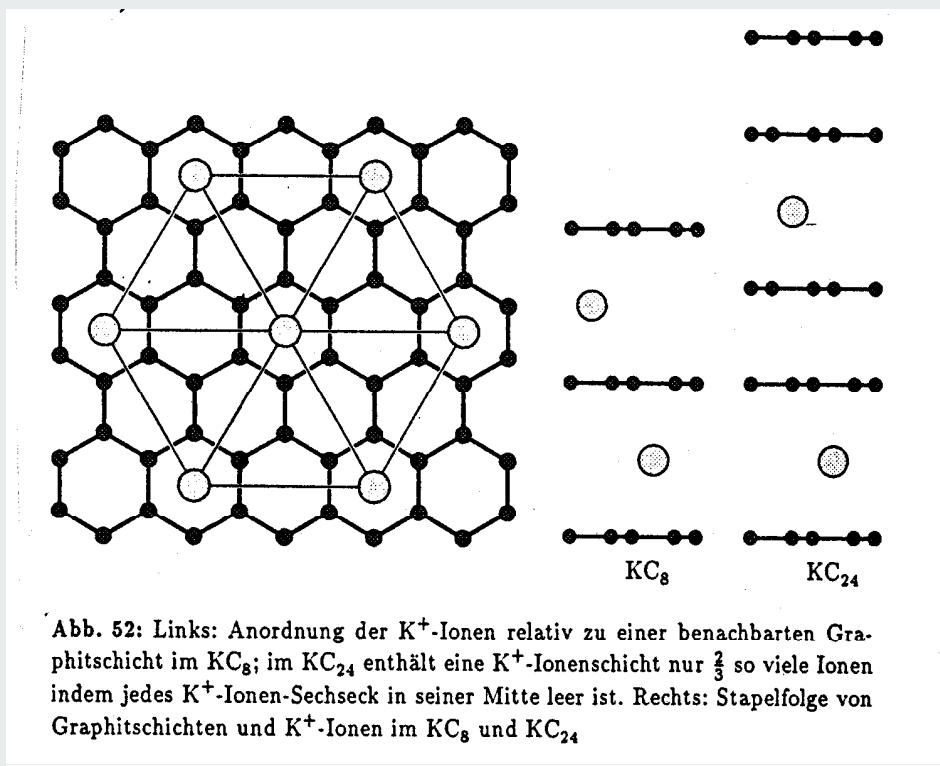


Abb. 52: Links: Anordnung der K⁺-Ionen relativ zu einer benachbarten Graphitschicht im KC₈; im KC₂₄ enthält eine K⁺-Ionenschicht nur $\frac{2}{3}$ so viele Ionen indem jedes K⁺-Ionen-Sechseck in seiner Mitte leer ist. Rechts: Stapelfolge von Graphitschichten und K⁺-Ionen im KC₈ und KC₂₄

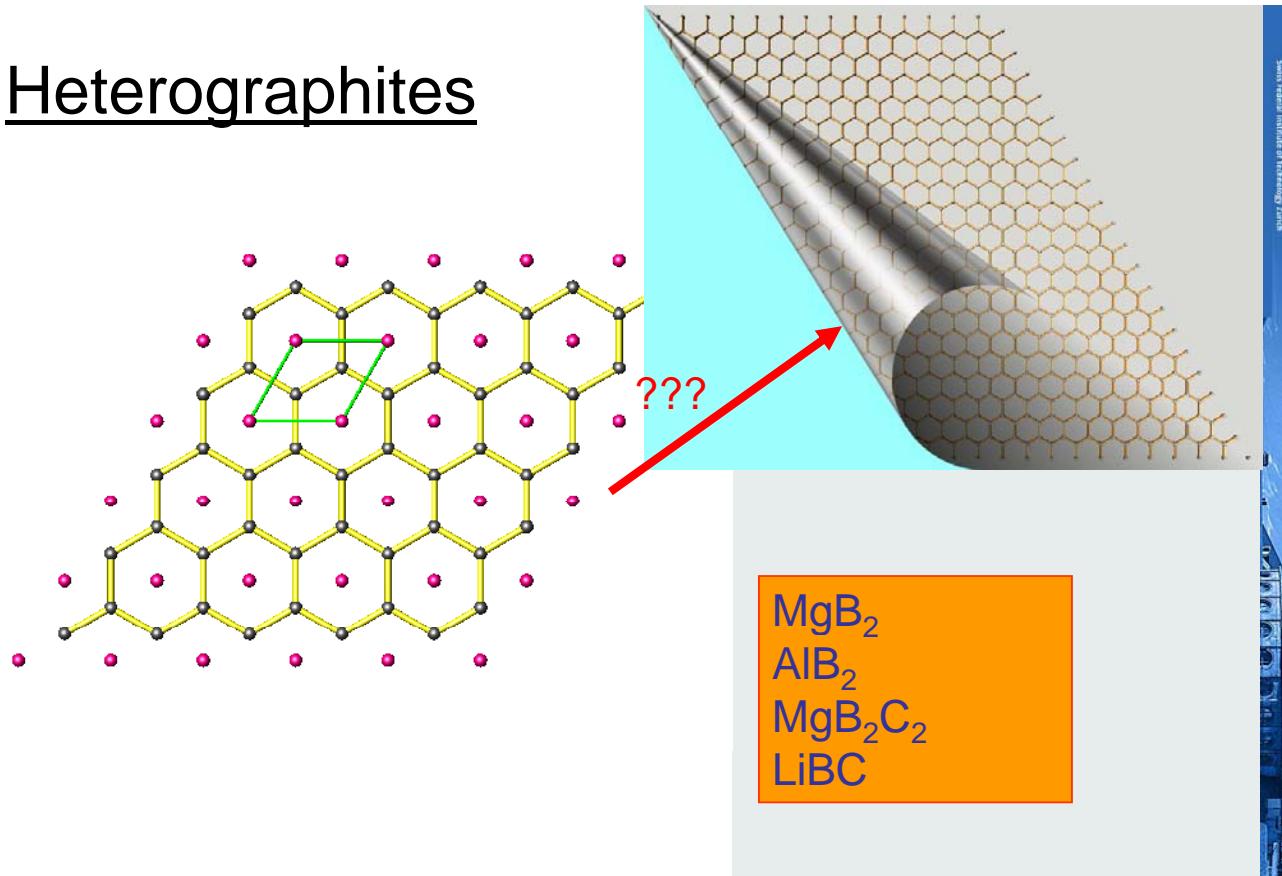
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Heterographites



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Graphite-related Superconductors

The superconducting materials demonstrate a **zero electrical resistivity** in a certain range of temperature, current and magnetic field.

Their maximum values are called:

critical temperature (T_c)

critical current density (J_c)

critical magnetic field (H_c)

MgB_2

MgB_2C_2

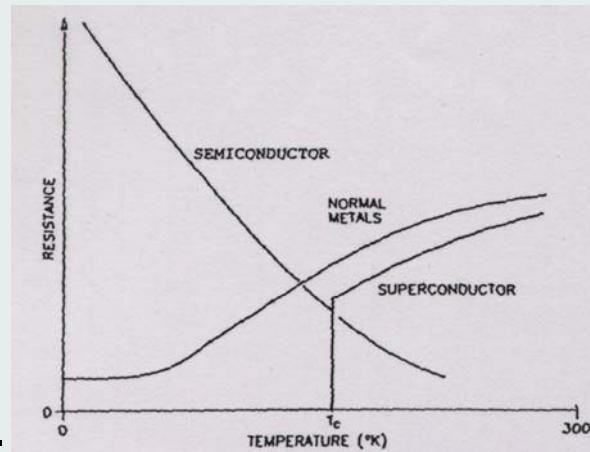
$LiBC$

AIB_2

Ca_x -graphite

Yb_x -graphite

$Li_{0.5}BC$ " $T_c=90K$

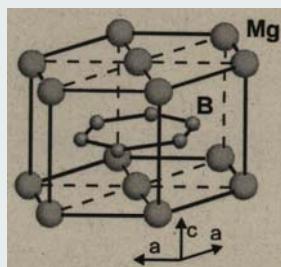


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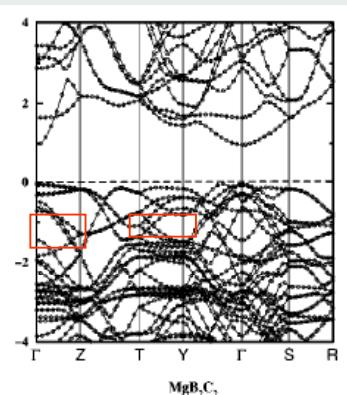
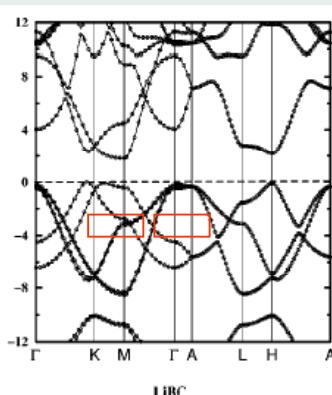
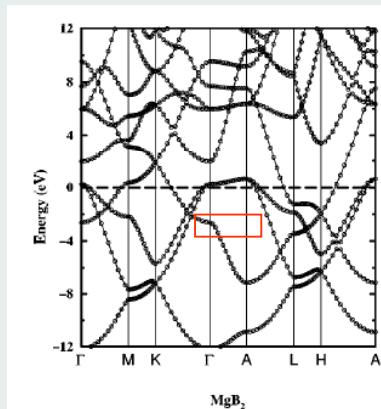
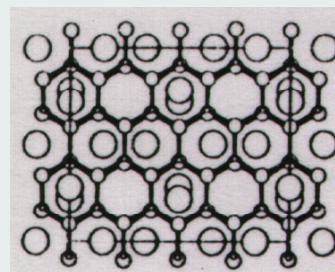
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Superconductivity - MgB_2 vs LiBC and MgB_2C_2



MgB_2
 MgB_2C_2
 $LiBC$
 $Li_{0.5}BC$ $T_c=90K$

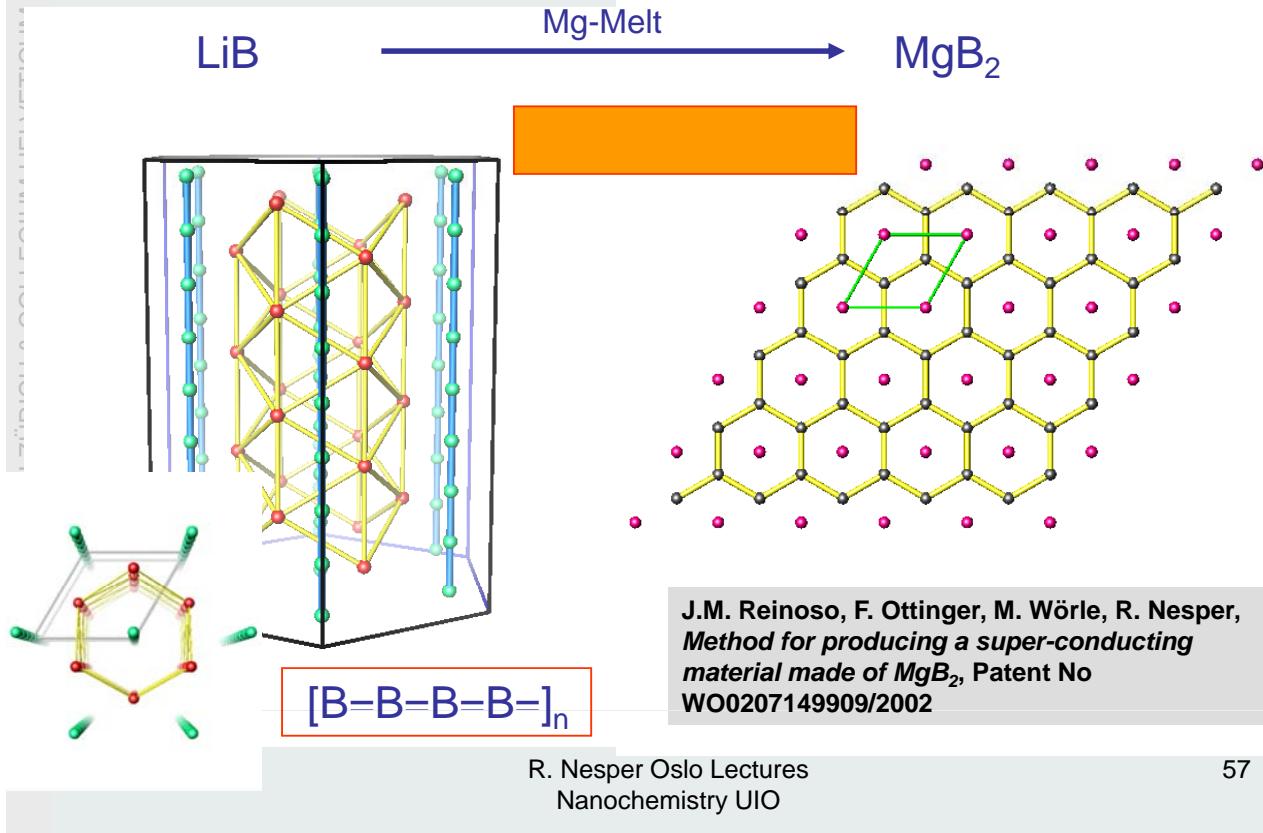


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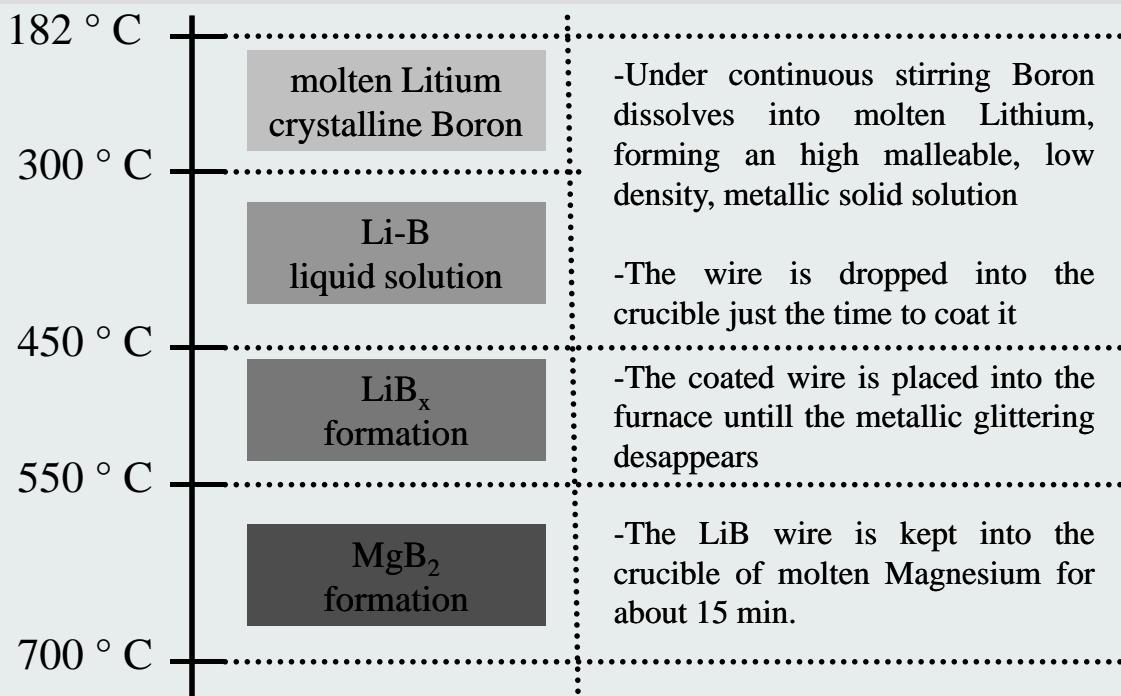
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MgB₂ and its Analoga Wire Preparation ?



Morphologie Preserving Transformation



- Sublimation of Mg / Mg_xLi_y under High vacuum, 630°C , 8 h

Preparing Wires and Rods

Li-B mixture



LiB_x compound



MgB₂



- The inner part does not react completely

- The resulting coating is highly porous

- Formation of oxidic layer can occur between the wire and the coating

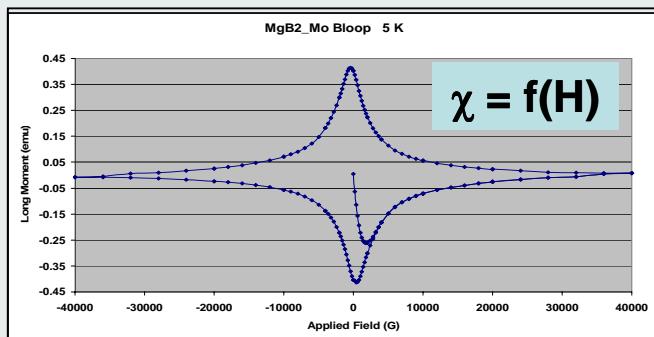
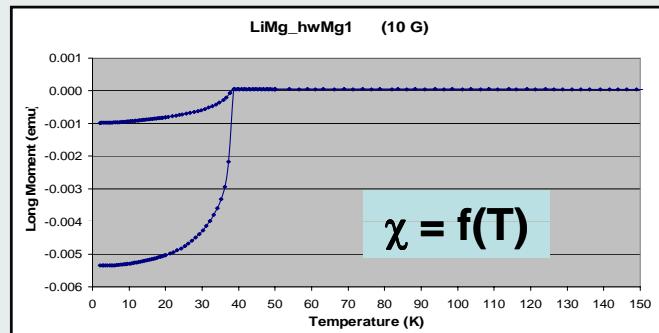
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Magnetic Measurements

pure MgB₂



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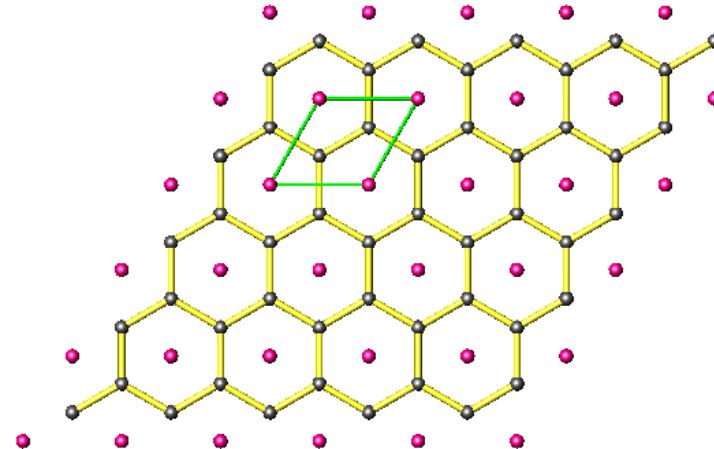
60

Heterographites –

MgB₂
MgB₂C₂
LiBC

„Li_{0.5}BC“ T_c=90K

???



Scrolled Ionic Compounds ?

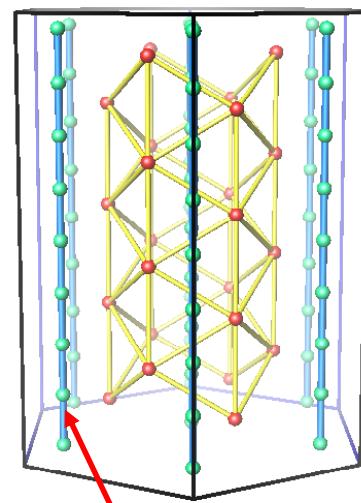
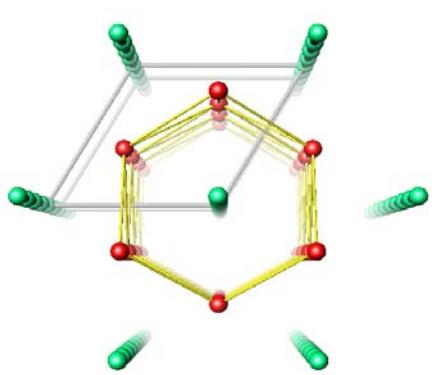
61



Chaoite – Substitute ?

LiB_{0.89}

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[B=B=B=B=]_n

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