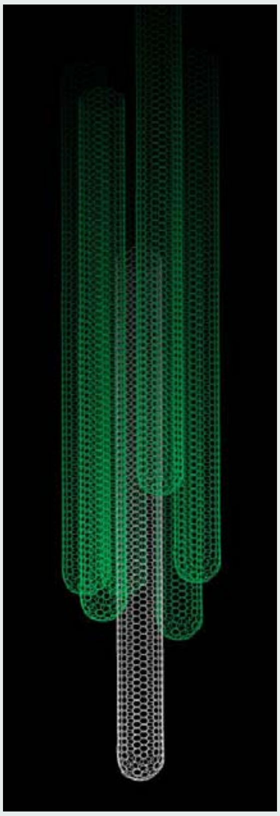
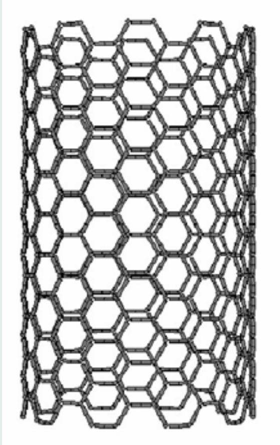
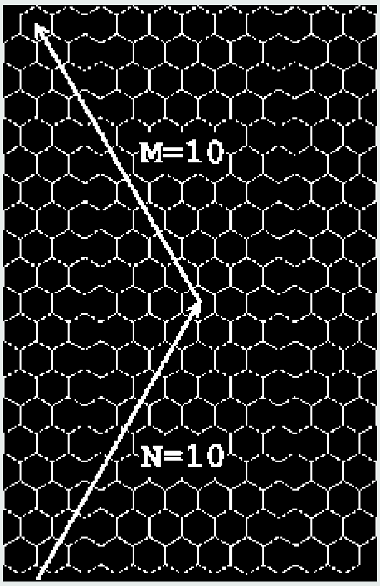
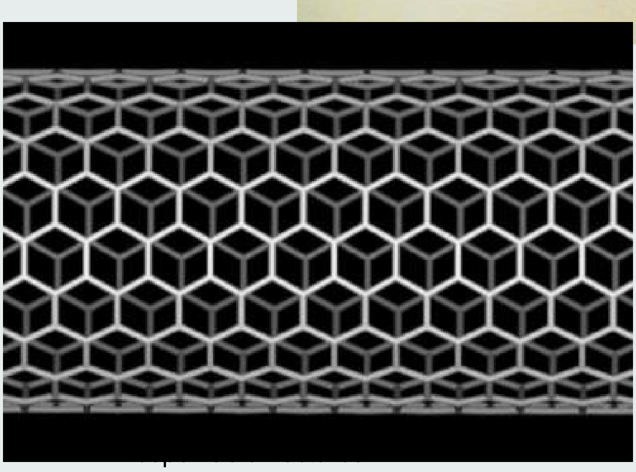
Carbon Nanotubes - CNTs





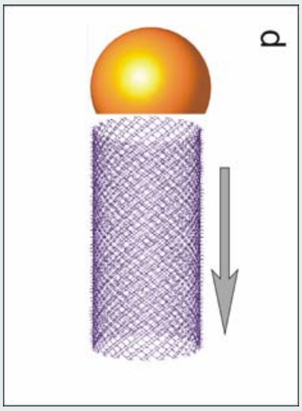
SWCNTs - Single Wall Carbon Nanotubes

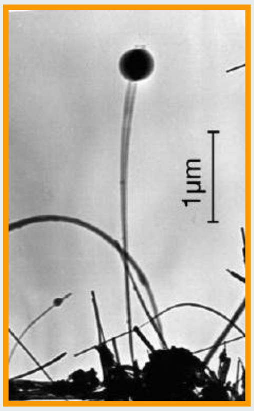


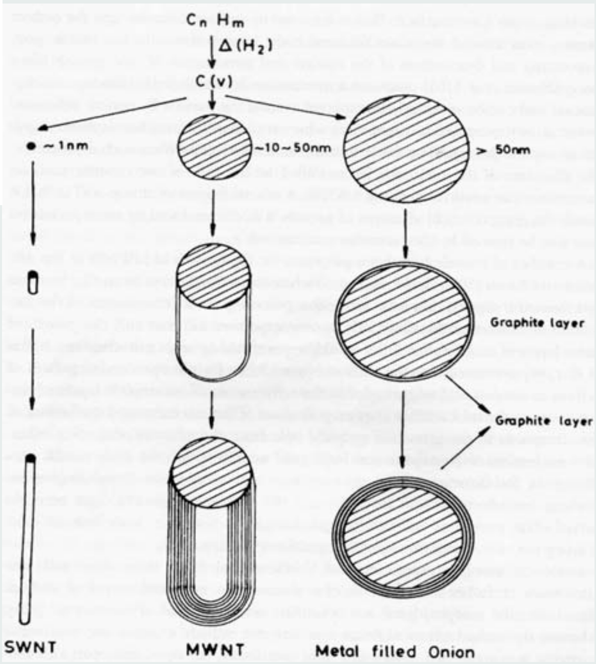


Carbon Nanotubes - Growth

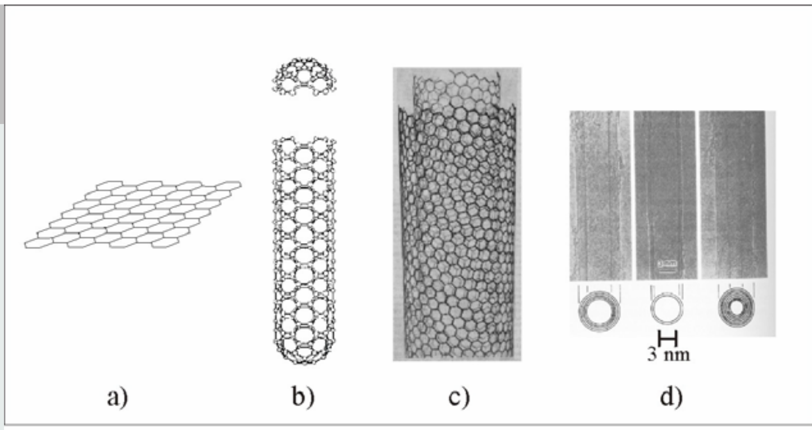
good physical and chemical properties.[1–3] Various methods for the synthesis of CNTs have been reported: arc-discharge,[3,4] laser ablation,[5] chemical vapor deposition,[6–10] flame synthesis,[11] and Smalley's recent invention of the high-pressure carbon monoxide (HIPCO) process.[12] However, none 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

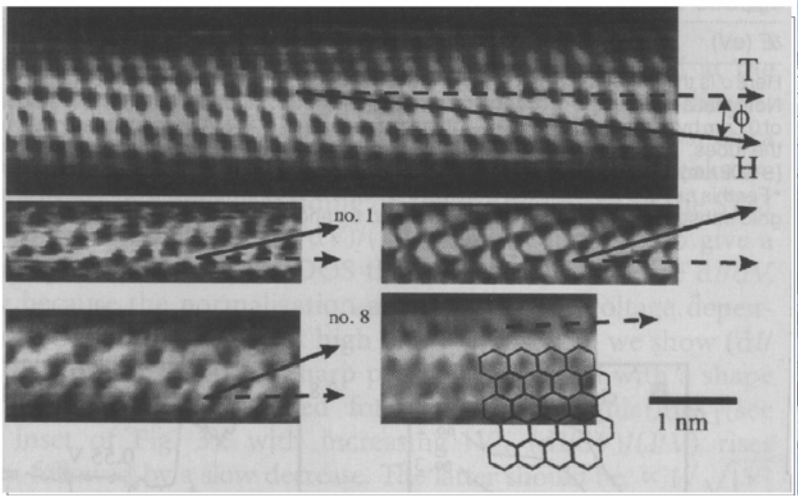






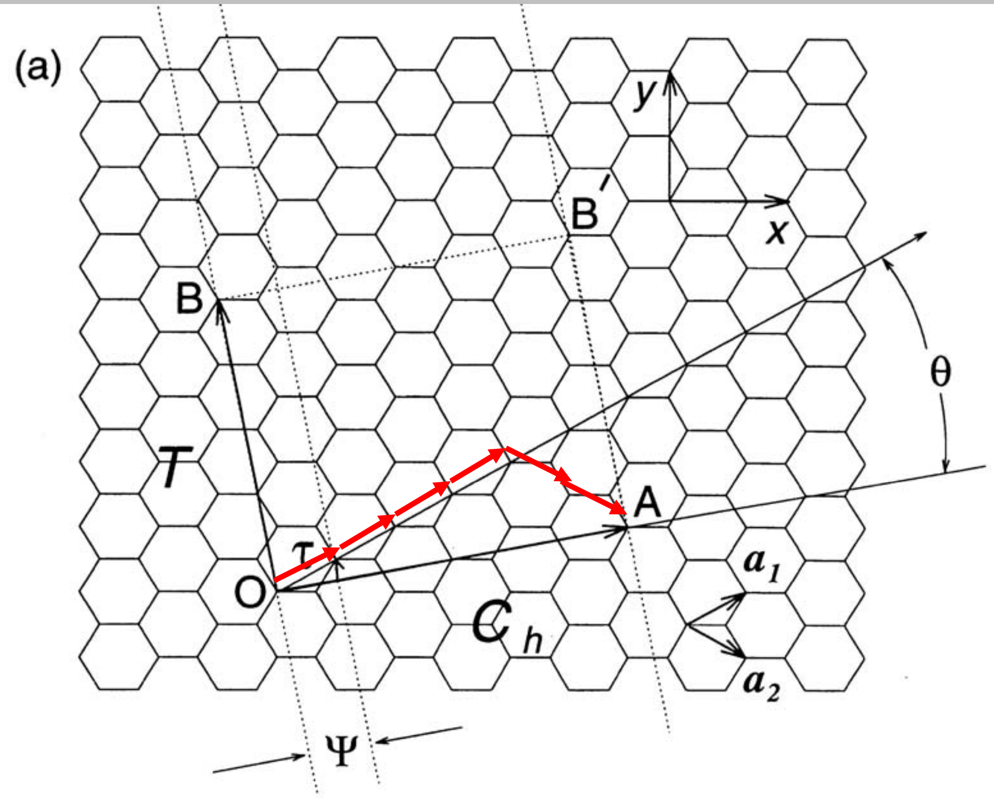
Carbon Nanotubes – Building Principles





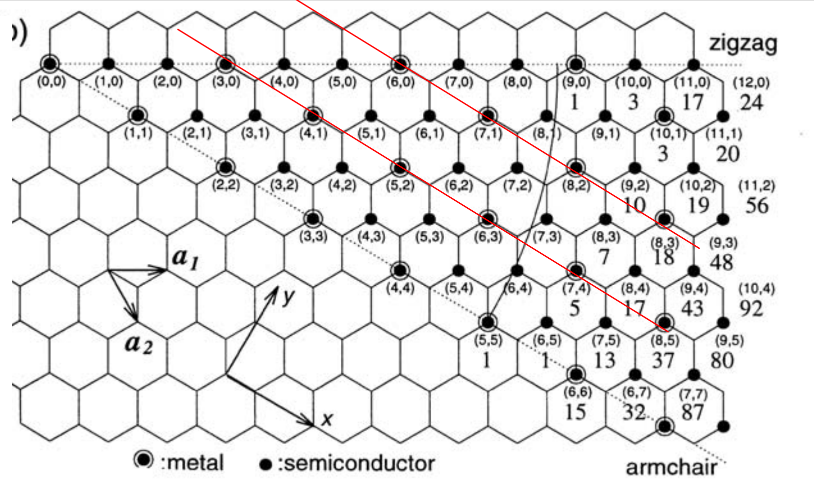
Carbon Nanotubes – Building Principle

R. NESPER ETH ZÜRICH & COLLEGIUM HELVETICUM



Carbon Nanotubes – Building Principle

R. NESPER ETH ZÜRICH & COLLEGIUM HELVETICUM



. 19.2. (a) The chiral vector $\overrightarrow{OA}$ or $C_h = na_1 + ma_2$ is defined on the honeycomb of carbon atoms by unit vectors a_1 and a_2 and the chiral angle θ with respect to gzag axis. Along the zigzag axis, $\theta = 0°$. Also shown are the lattice vector $\overrightarrow{OB} = T$ of D 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) = (4, 2). (b) Possible vectors specified by the pairs of integers (n, m) for general carbon s, 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 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 Principles

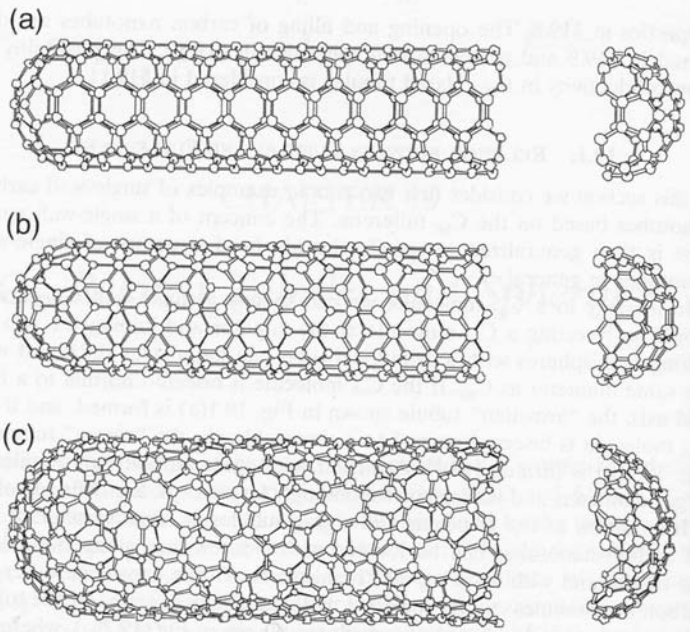


Fig. 19.1. By rolling a graphene sheet (a single layer from a 3D graphite crystal) into a cylinder and capping each end of the cylinder with half of a fullerene molecule, a "fullerene-derived tubule," one atomic layer in thickness, is formed. Shown here is a schematic theoretical model for a single-wall carbon tubule with the tubule axis normal to: (a) the $\theta = 30°$ direction (an "armchair" tubule), (b) the $\theta = 0°$ direction (a "zigzag" tubule), and (c) a general direction $0 < \theta < 30°$ (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].

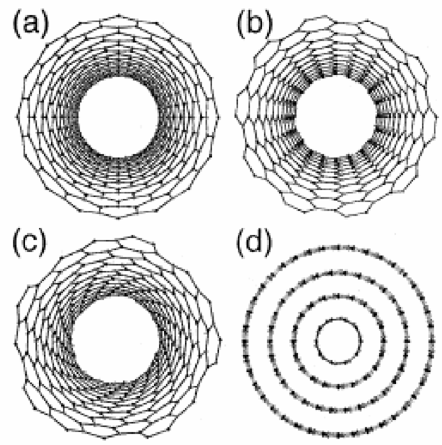


Fig. 1. Models of different nanotube structures. (a)–(c) are SWNTs of 1.25 nm diameter of (a) zig-zag, (b) armchair, and (c) chiral type. (d) represents a MWNT formed by four armchair tubes of increasing diameter with an interlayer separation of 0.34 nm. The image has been reduced by a factor of 2 with 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.

Dynamics of C-NTs

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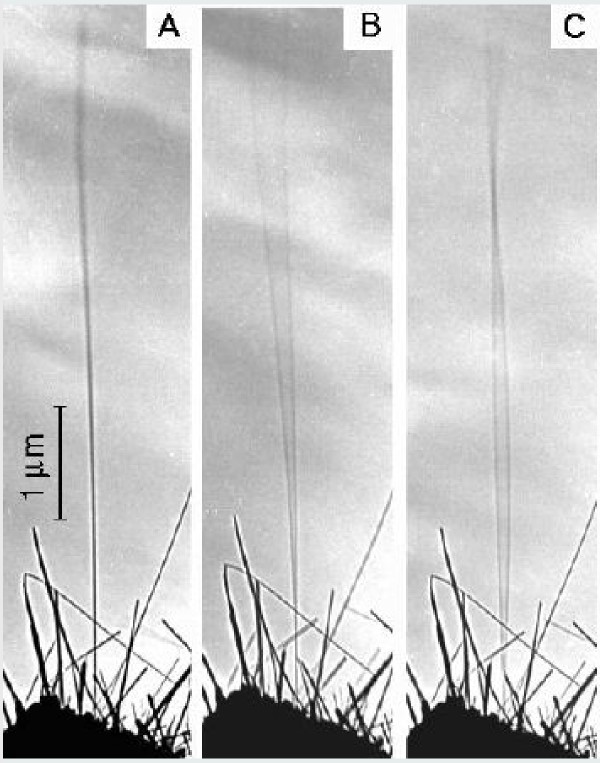
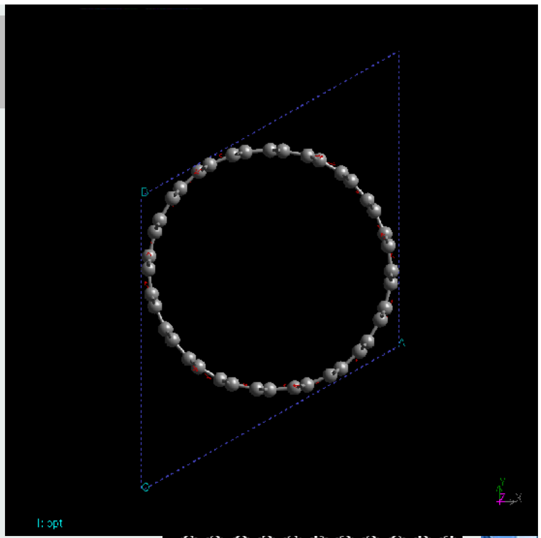
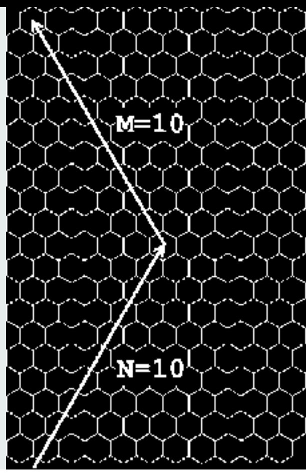
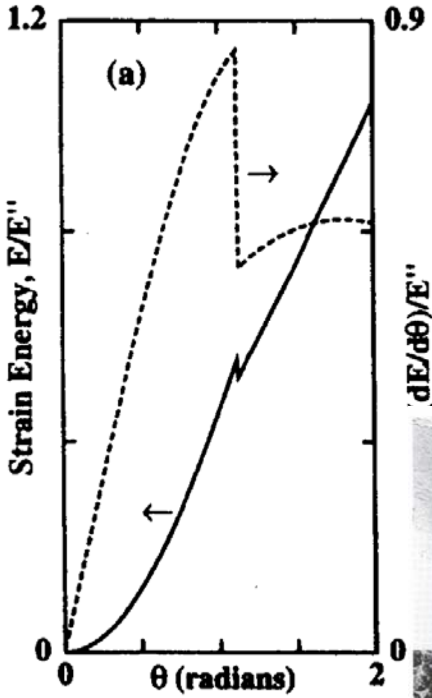
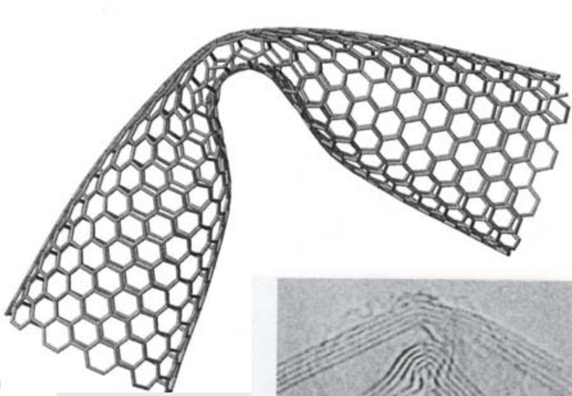


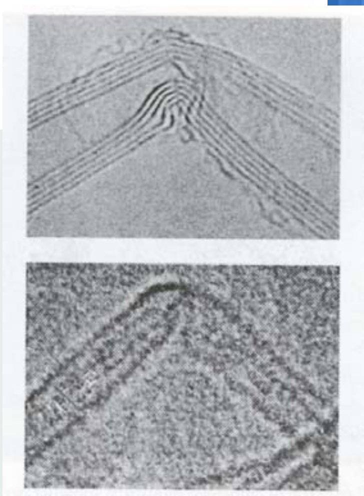


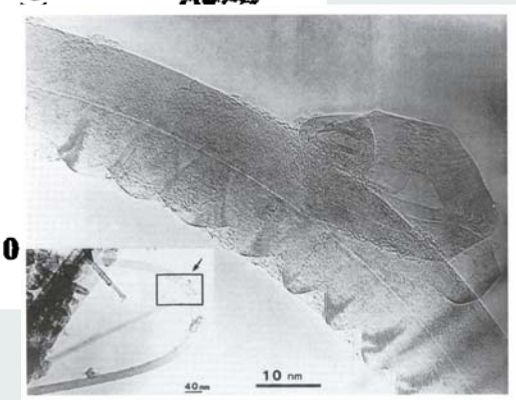


Strength of CNTs

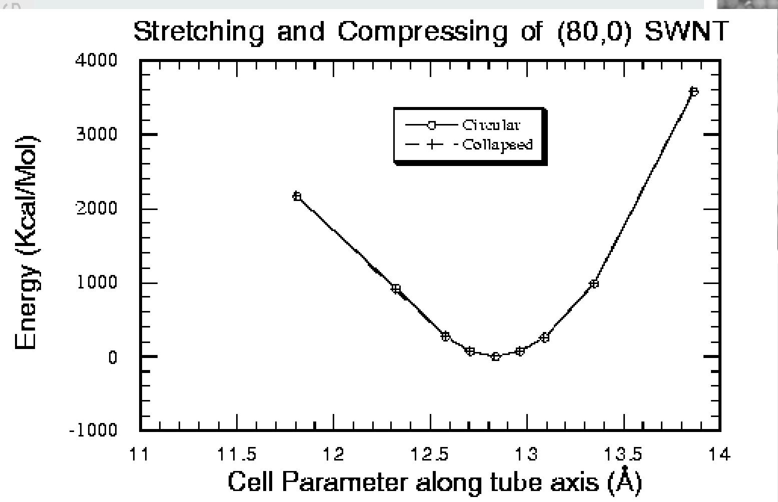


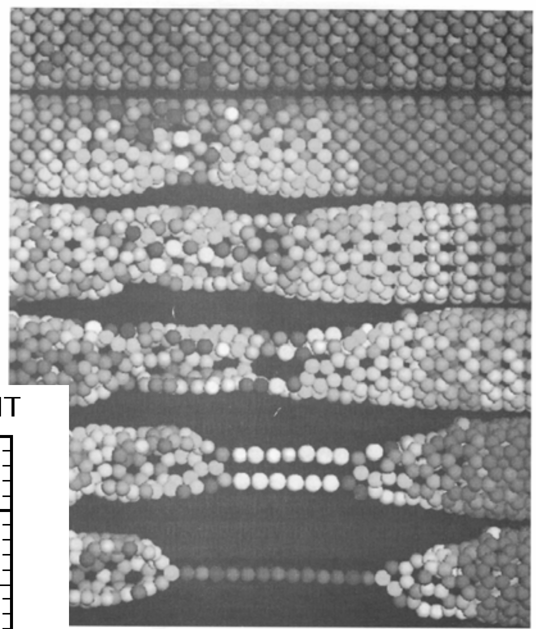






Strength of CNTs





SWCNT – Plastic Deformation

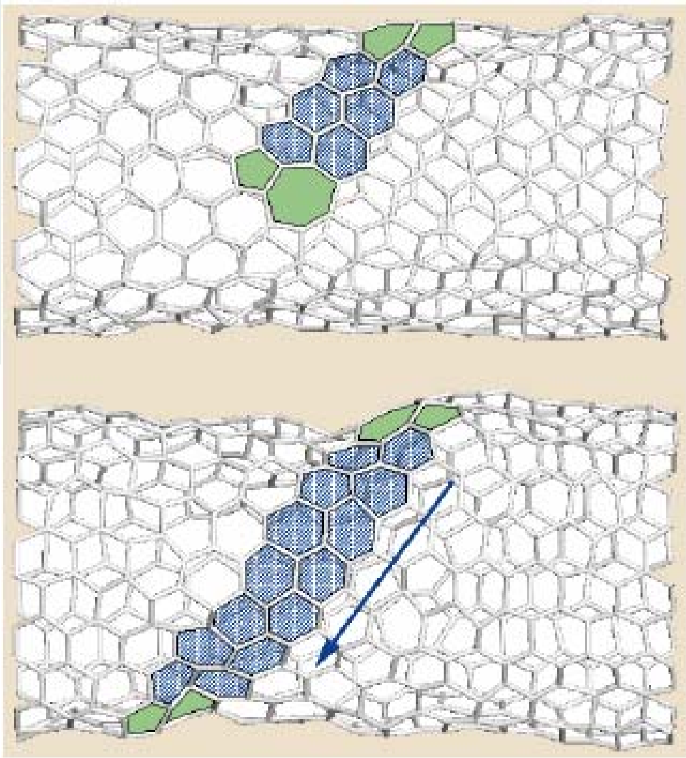


Figure 1 Plastic deformation of a carbon nanotube. Molecular dynamics simulations of a (10,10) nanotube under axial tension (J. Bernholc, M. Buongiorno Nardelli and B. Yakobson). Plastic flow behaviour is shown after 2.5 ns at $T = 3{,}000$ K and 3% strain. The blue area indicates the migration path (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).

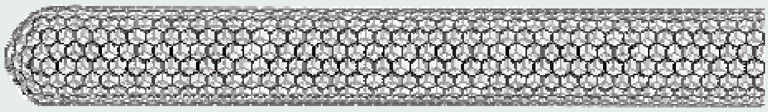
Carbon Nanotubes

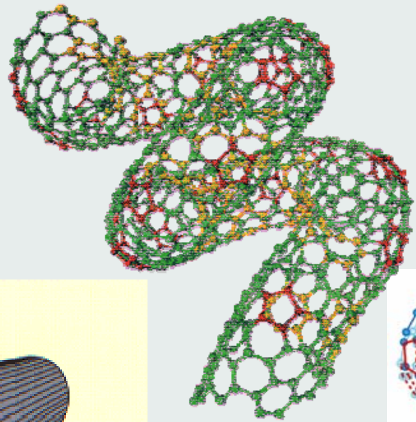
http://www.pa.msu. edu/cmp/csc/nanotube.hmtl

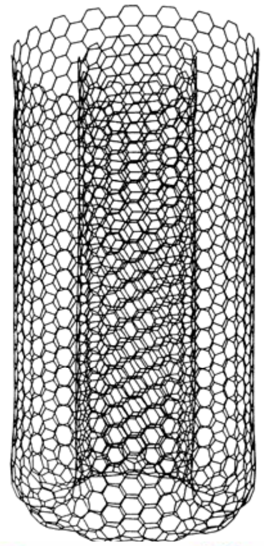
Characterization of each individual set of nanoparticles necessary

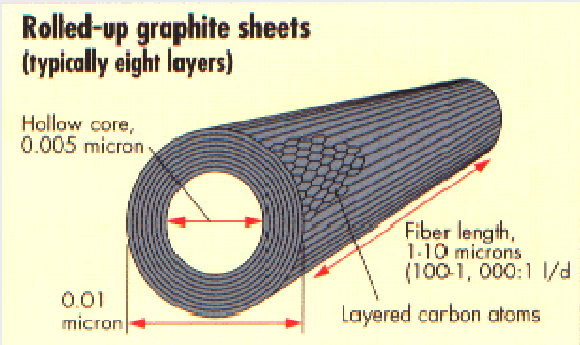
Density:	1.35 g/cm^3
Resistivity	10^{-4} wcm
Maximum Current Density	10^9 A/cm^2
Thermal Conductivity	~2000 W/mK
Relaxation Time	~10^{-11} s
Elastic Behavior	
Young's Modulus (SWNT)	~1 TPa
Young's Modulus (MWNT)	1.28 TPa
Maximum Tensile Strength	~100 GPa

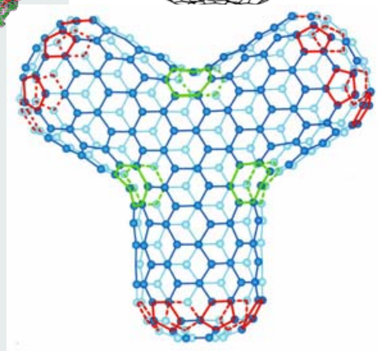
C-Nanotubes - Forms





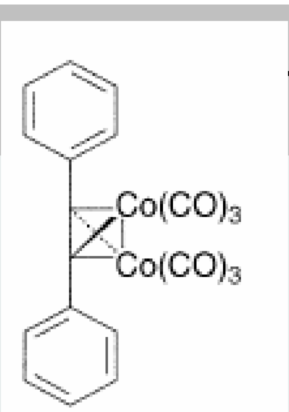


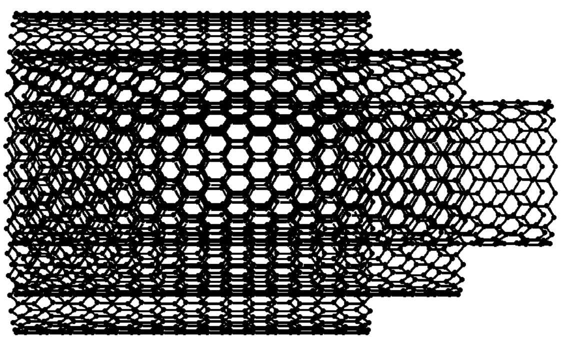




Multiwalled Carbon Nanotubes

Synthesis below 500 °C





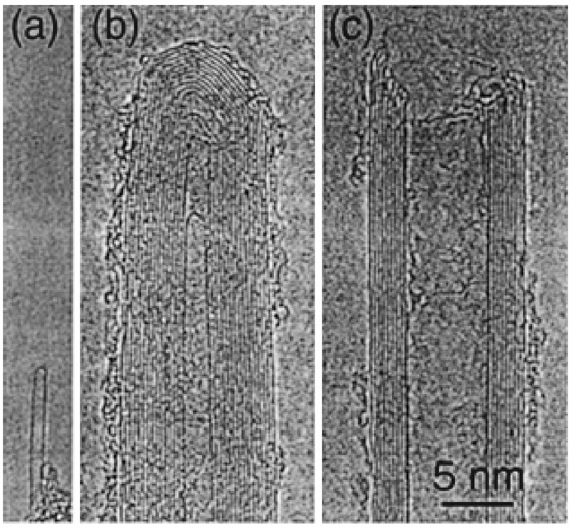
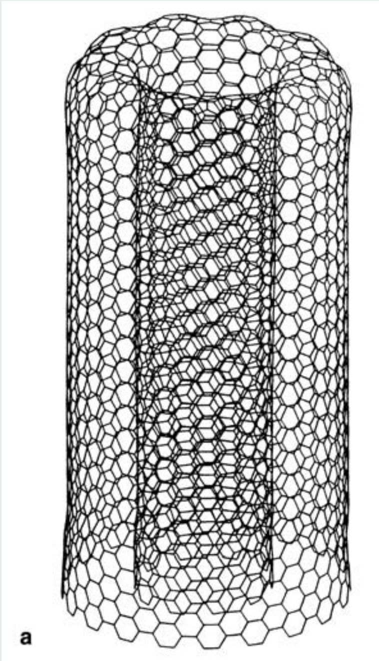


Fig. 2. TEM pictures of the ends of (a) a SWNT, (b) a closed MWNT, and (c) an open MWNT. Each black line corresponds to one graphene sheet viewed edge-on. The micrographs are reproduced at the same magnification.

D ~ 0.34 nm

C-Nanotubes – Multiwall Connections



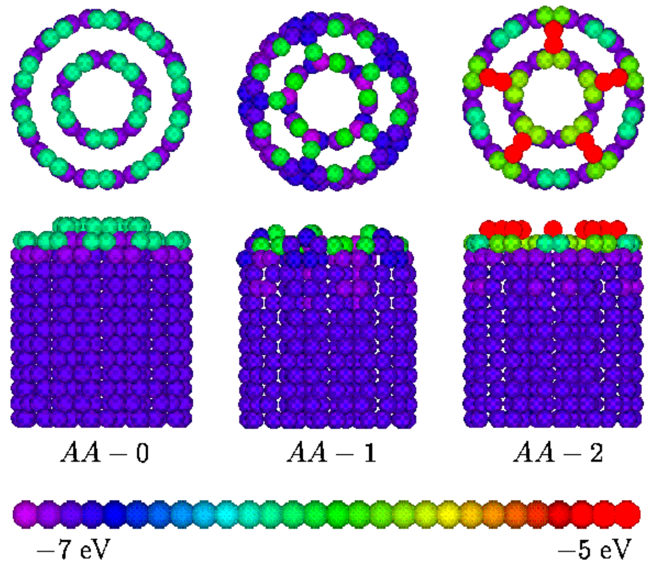
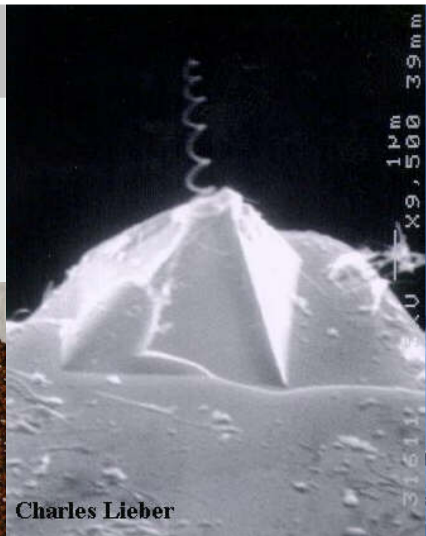


Figure 2

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

Helices, Springs, Actuators



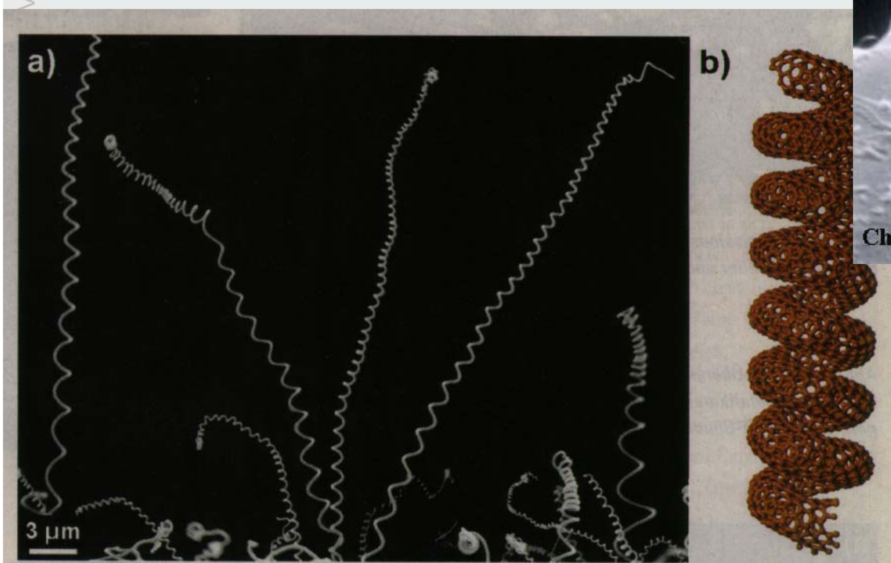


Abb. 6. a) Rasterelektronenmikroskopische (REM)-Aufnahme mehrerer pyrolytisch synthetisierter spiralförmiger Nanoröhrchen. b) Theoretisches Modell der korkenzieherartigen Gebilde.

Other new CNTs ?

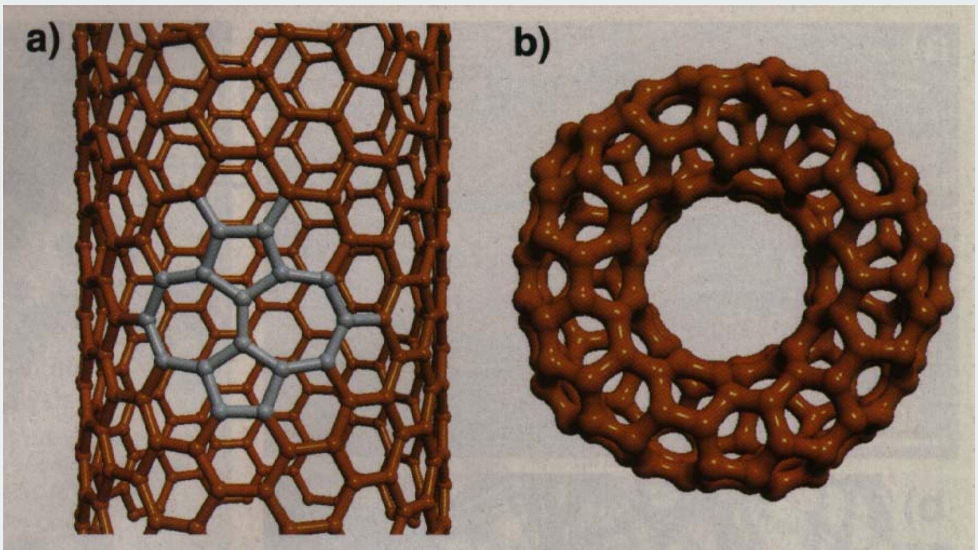
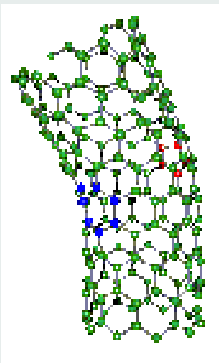
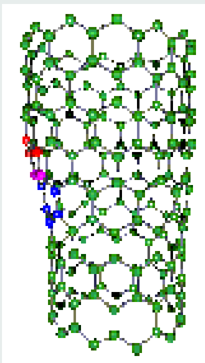
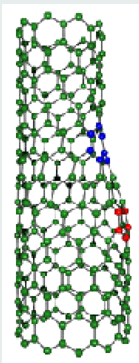
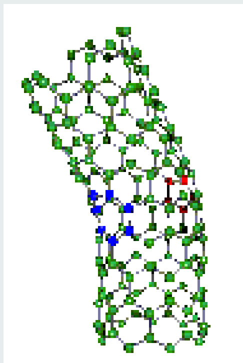
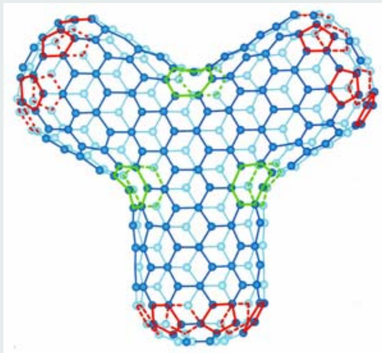
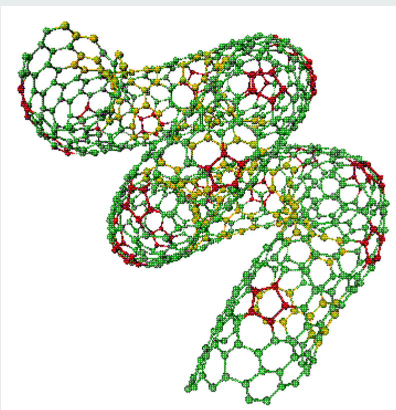


Abb. 5. a) Modell eines einwandigen Kohlenstoff-Nanoröhrchens mit einem 5,7-Defekt, der aus vier Sechsecken über eine Stone-Wales-Transformation entsteht. b) Durch den Einbau von Fünf- und Siebenekken an bestimmten Stellen entsteht ein ringförmiges Nanoröhrchen; hier schematisch dargestellt. (Bild: Dr.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

Building Faults, Properties, Electronics

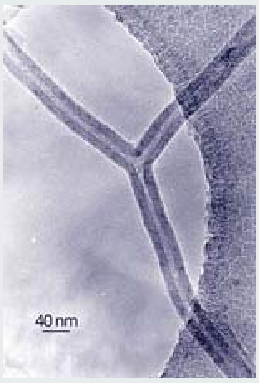







5+7 ring => Diode

But contact resistance !!

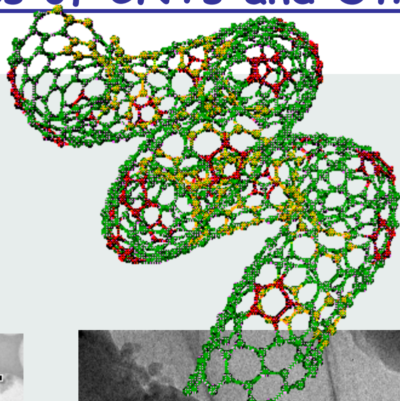
Semicond. / metallic CNT transistor

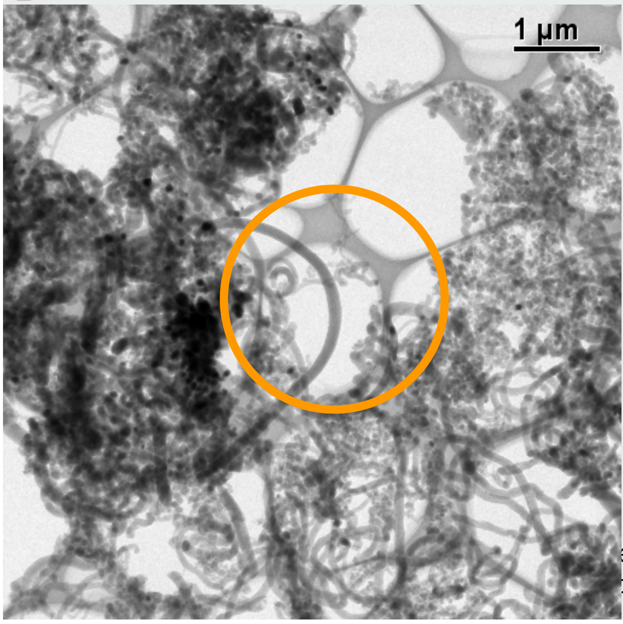
But no control on helicity!!

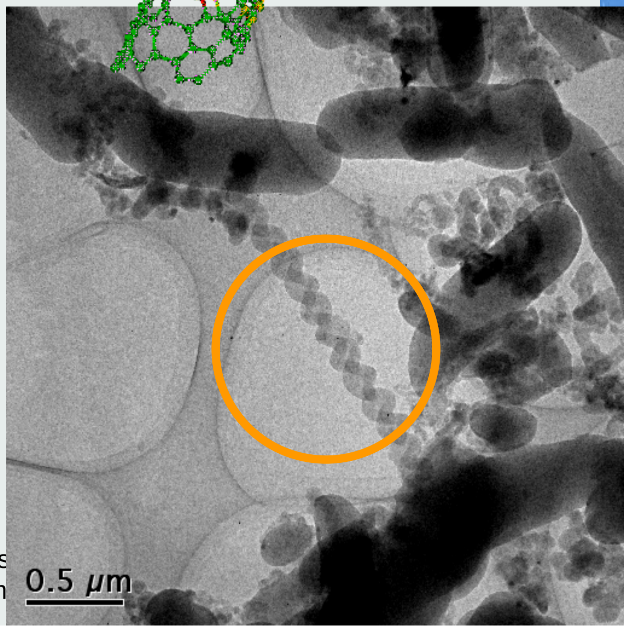


Low Temperature Syntheses of CNTs and Other C Nanoparticles

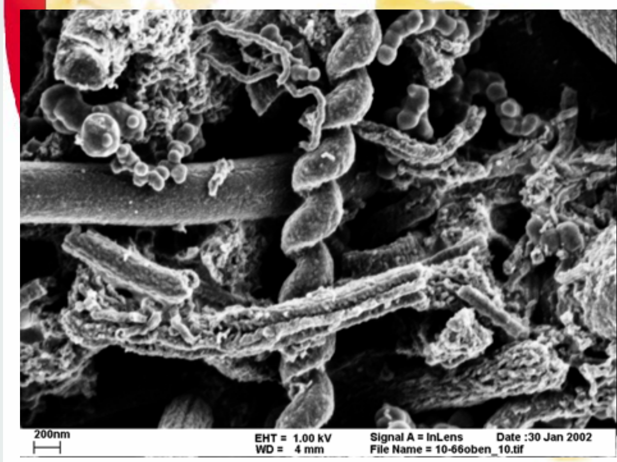
T < 500 C

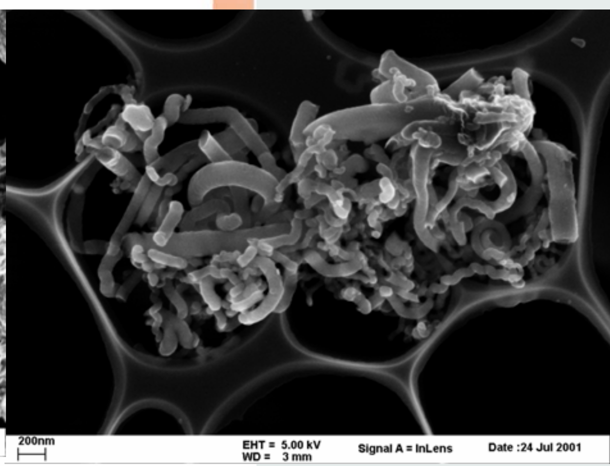




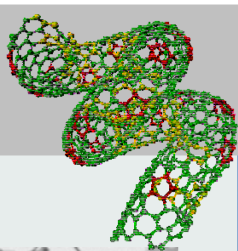


Carbons – All Pasta and Infinite Set ?

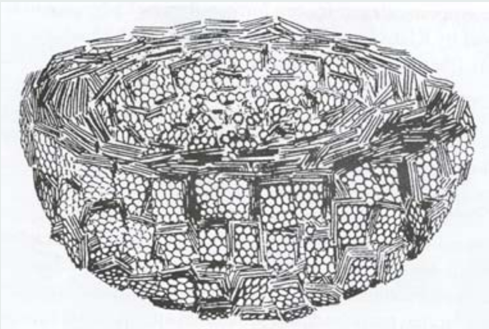


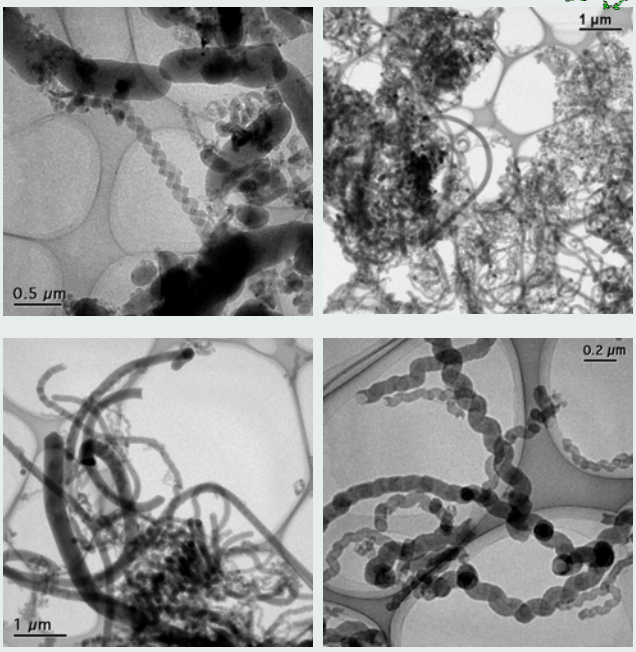


Low Temperature Syntheses of CNTs and Other C Nanoparticles



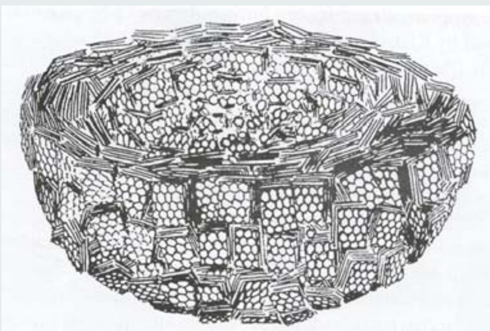
Fish bone structures





Low Temperature Syntheses of CNTs

Fish bone structures



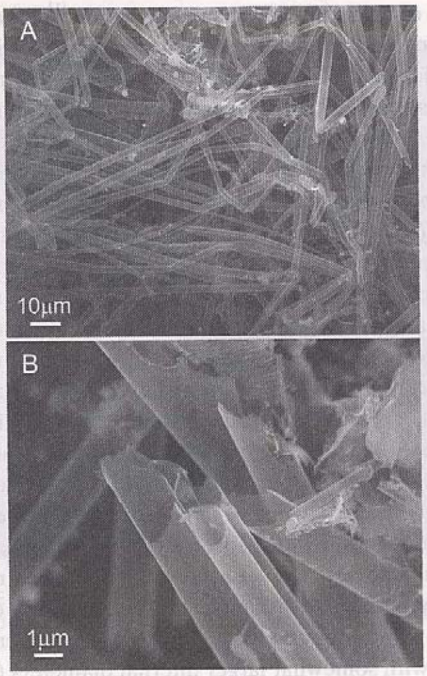
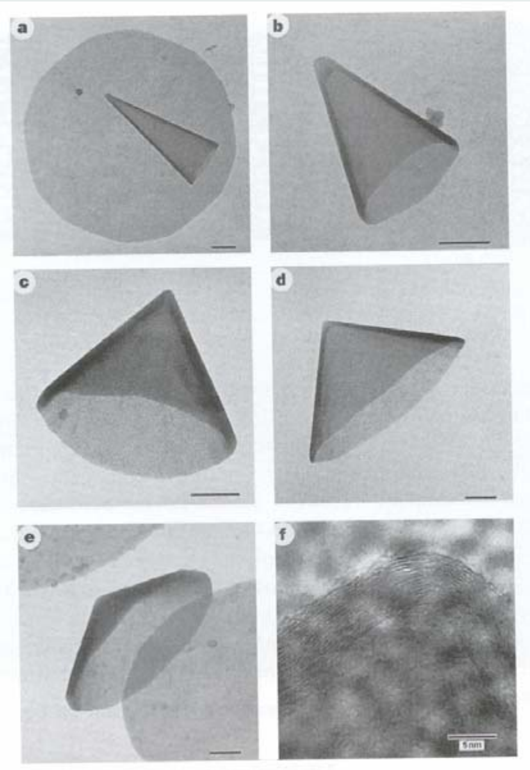


Figure 1. A) Low-magnification SEM image of the carbon microtubes. B) High-magnification SEM image displaying the open ends of the microtubes.

Cones, Bamboos etc.

A. Ivantchenko, R. Nesper



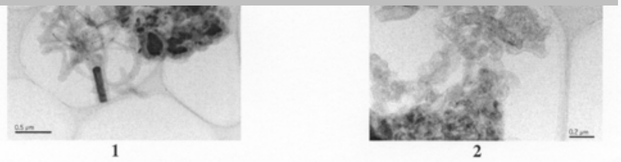


Fig.2 Carbon microstructures obtained (1)after washing with 65% nitric acid (2)after washing with acid and heated to ~~1000~~ 1400^{0}C in Ar atmosphere

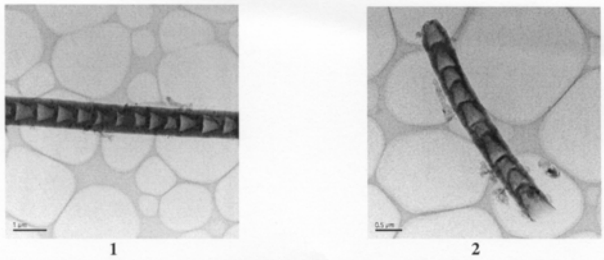
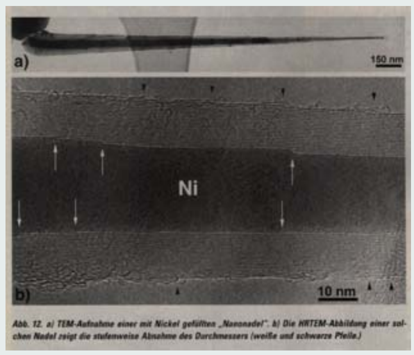


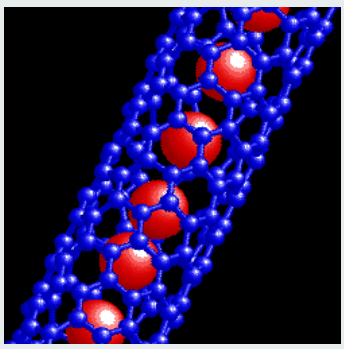
Fig.3 Carbon microstructures obtained (1)after washing with 65% nitric acid (2)after washing with acid and heated to ~~1000~~ 1400^{0}C in Ar atmosphere

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

Storage in CNTs

In a recent work of Baker and Rogriguez [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.





H_2 – Storage in C-NTs ?

wrong !! ➔

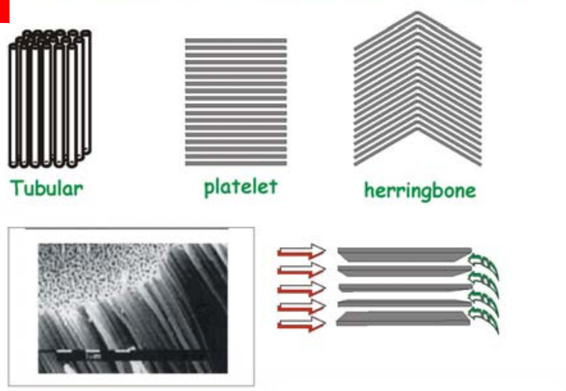
Baker, N. Rodriguez et al., J.Phys.Chem. B 102, 423 (1998)

Baker & Rodriguez

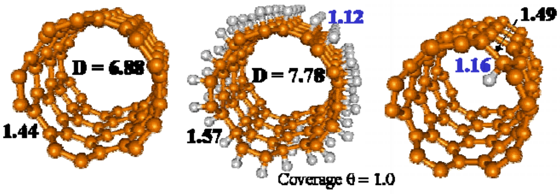
65wt% ‼???

M. Parrinello

max. 14wt%



Hydrogen adsorption on (5,5) SWNT



< Binding energy (eV/bond) >

	C-C	C-H	C-H
DFTB	-9.14	-2.65	-0.83
LDA	-8.41	-2.10	-1.50
GGA	-7.48	-1.75	-1.28

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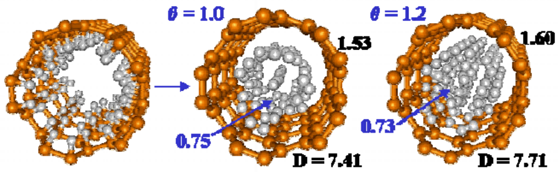
Hydrogen storage in (5,5) SWNT



	DFTB (LDA:GGA)	DFTB
• Binding energy (eV/H_2)	-4.57 (-3.16:-2.24)	-4.01
• Wall-H_2 repulsive energy (eV/H_2)	0.70 (0.47:0.74)	0.78
• H_2-H_2 repulsive energy (eV/H_2)	0.89 (0.81:1.19)	1.11

• H_2 molecules exist inside nanotubes.
• H_2 can be stored inside nanotubes with coverage > 1.0.

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Catalyst Patterning for Growth of CNTs

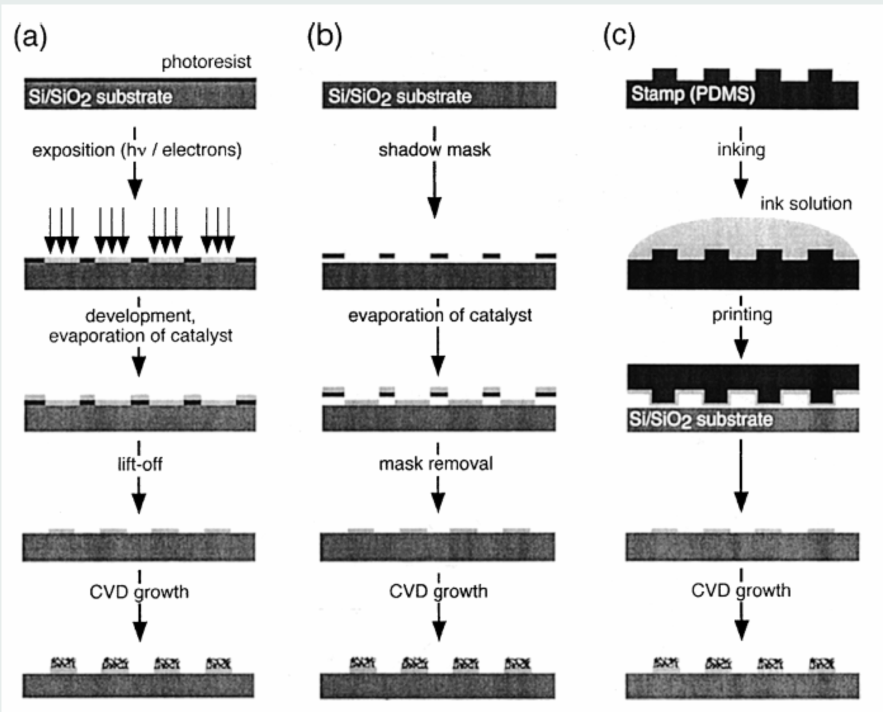


Fig. 4. Techniques to produce patterns of catalysts for the selective growth of carbon nanotubes: (a) standard lithography, (b) shadow-masking, (c) soft lithography.

Hierarchical Order – Aggregations

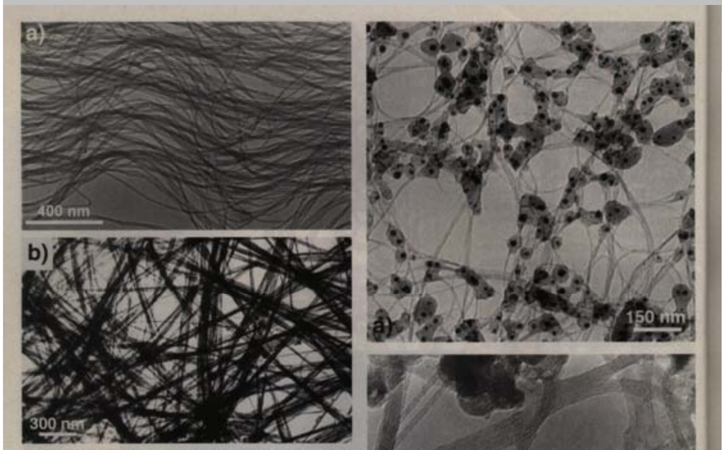
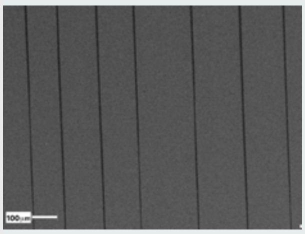


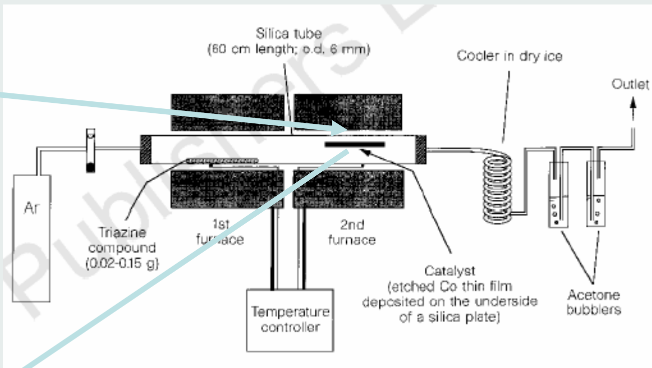
Abb. 8. Transmissionselektronenmikroskopische (TEM)-Aufnahme a) pyrolytisch gewachsener und b) im Lichtbogen hergestellter MWNTs.

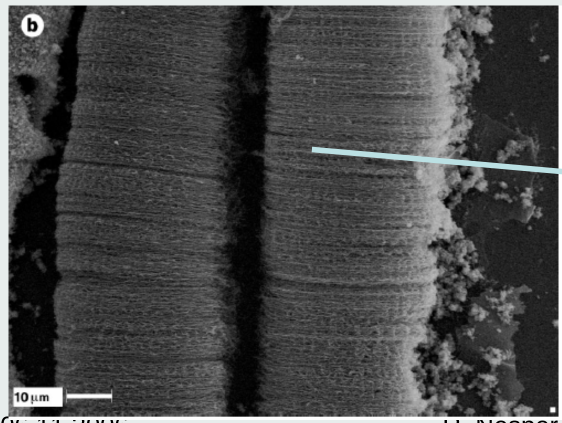
Abb. 9. a) TEM-Übersichtsaufnahme von SWNTs, die im Lichtbogen und dem Einsatz von Metallkatalysatoren synthetisiert wurden. b) Großaufnahme der in a) gezeigten SWNT-Bündel.

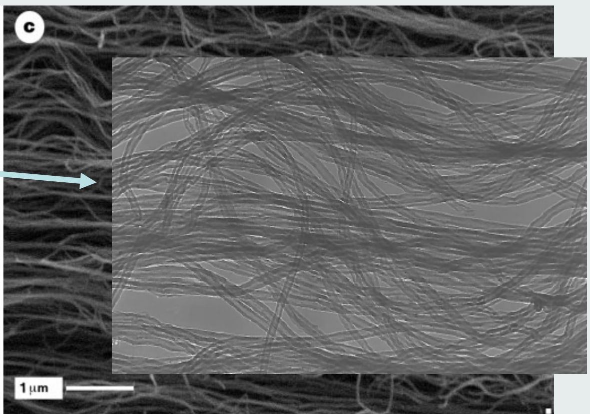
Abb. 10. a) REM-Aufnahme eines MWNT-Bündels, das während der Pyrolyse organischer Feststoffe gewachsen ist. b) Großaufnahme der ausgerichteten MWNTs dieses Bündels.

Hierarchical Order – Carpets Predefined









Hierarchical Order – Carpets etc.

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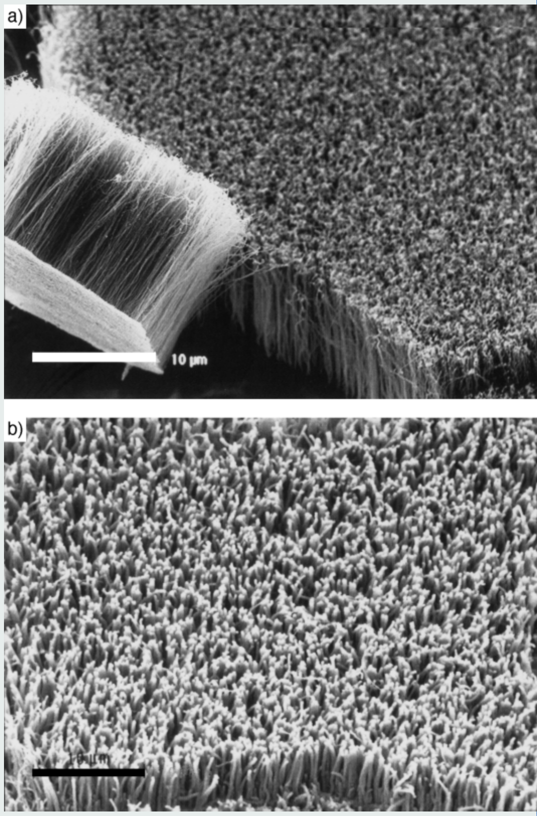
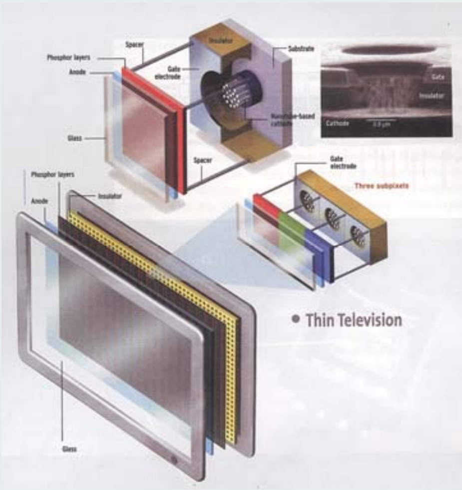
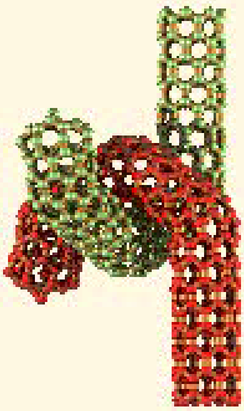
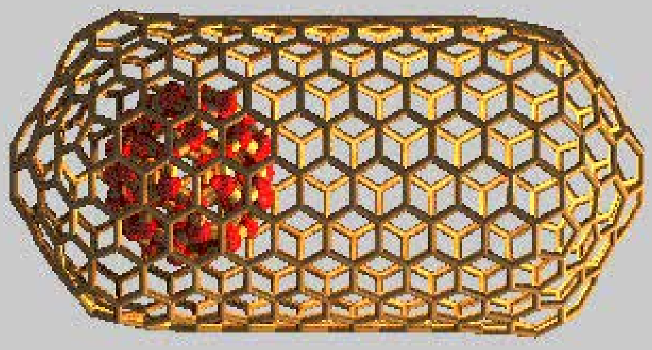




Carbon Nanotubes Models

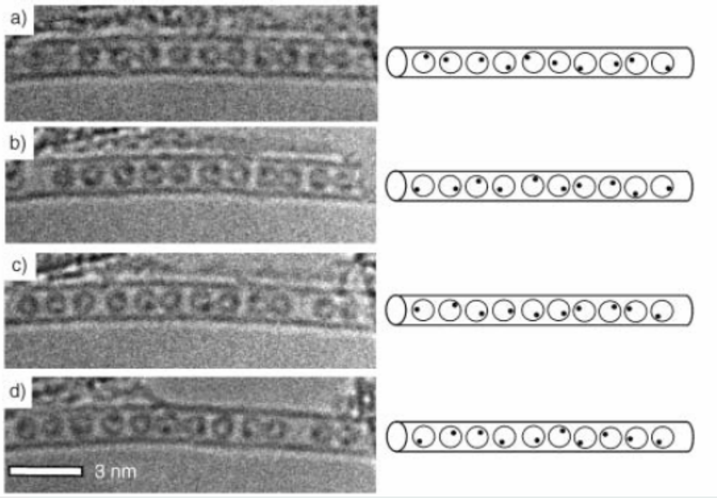
(http://www.pa.msu. edu/cmp/csc/nanotube.html)

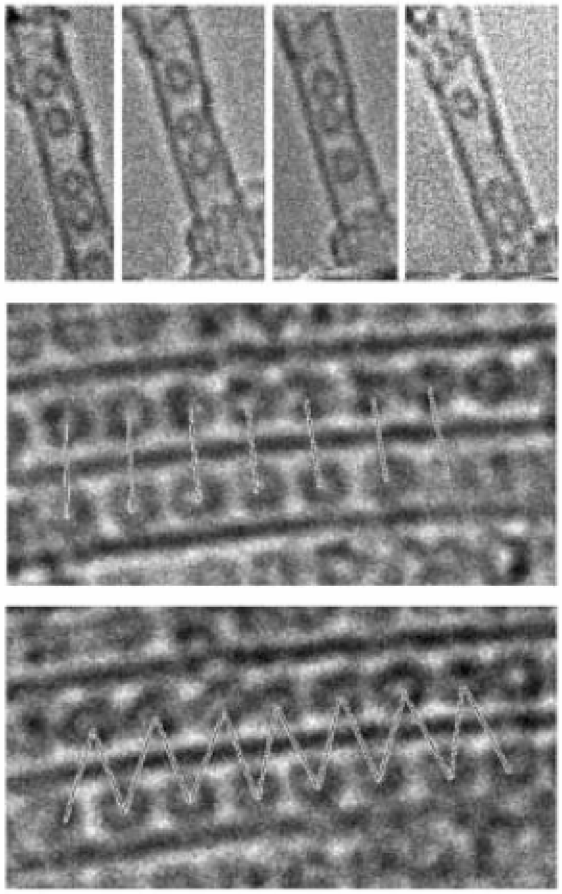




Filling of Carbon Nanotubes

$(Ce@C_{82})@SWNTs$





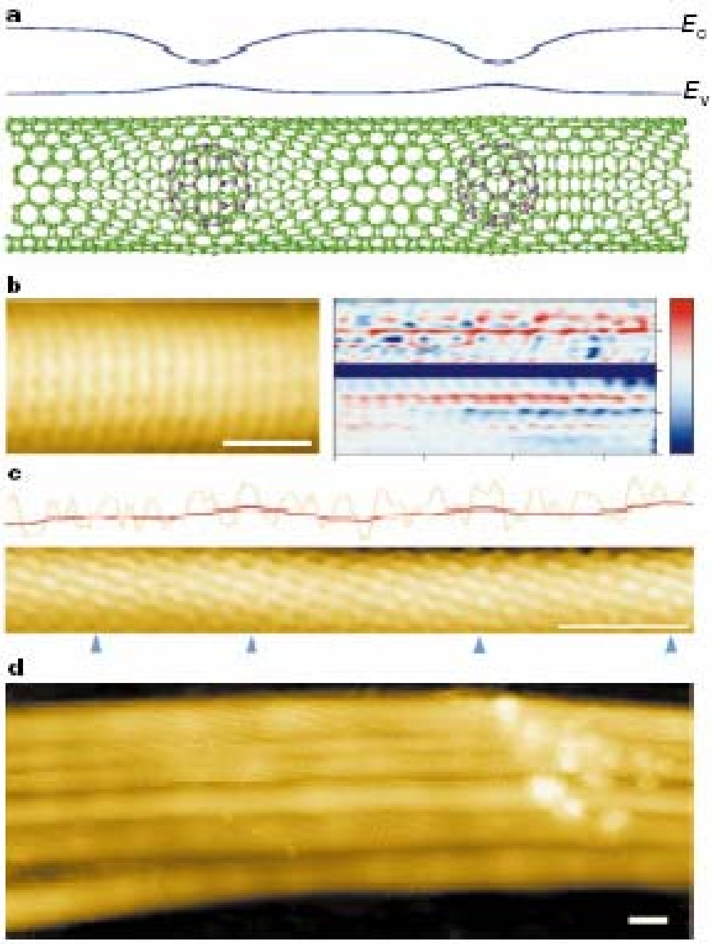
Valence & conduction bands

Elastic strain

STM topography

Atomic resolution

SWT bundle



Applications of CNTs - Thermocouple

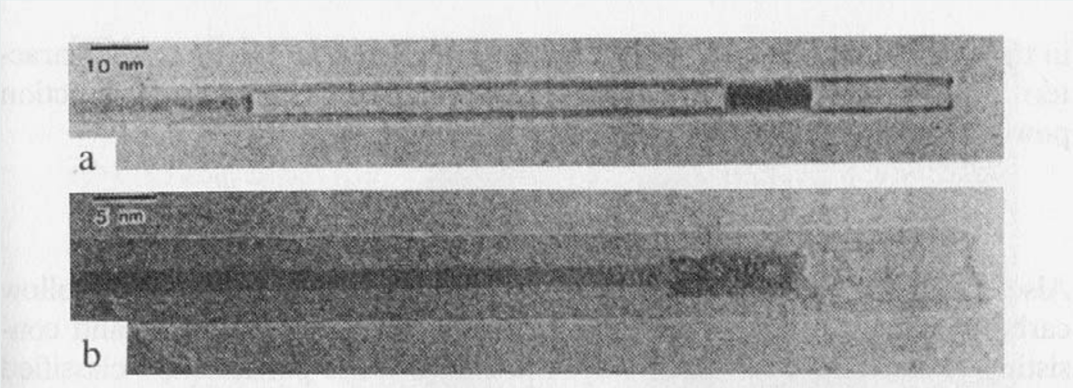
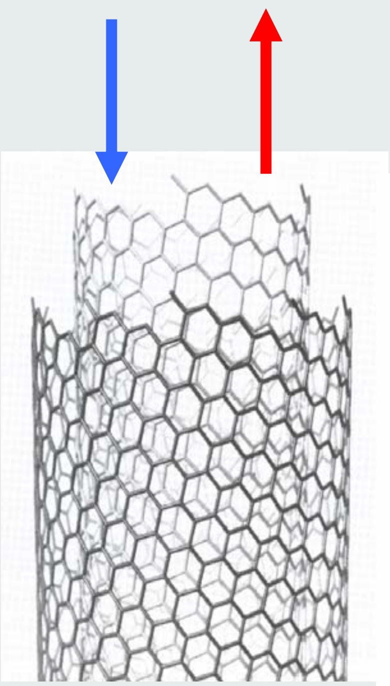


Fig. 19.60. TEM image of nested carbon nanotubes containing a Pb filled core [19.66].

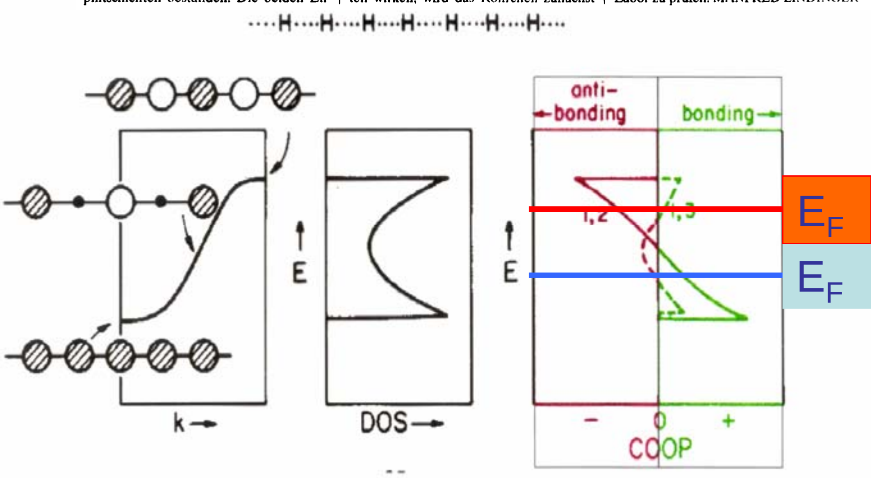
Tube-in-Tube



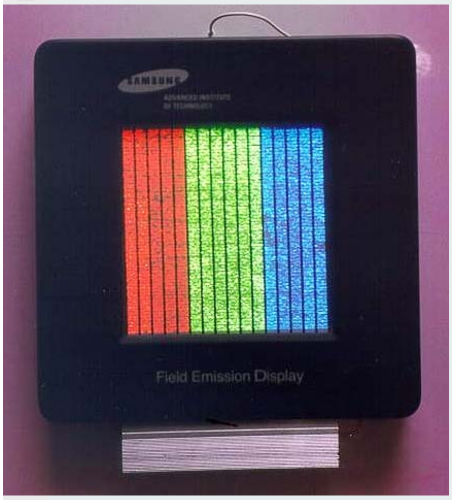

Flinkes Nanoröhrchen schwingt wie winziges Federpendel

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 entfernten die Kappe an einem Ende und ergriffen die inner- … wieder in das Innere der Graphithülle zurückgezogen. Dort besitzt es aber genügend kinetische Energie, am anderen Ende wieder herauszuschießen. Hat sich …

Foto Alex Zettl/University of California



Field Emission Displays



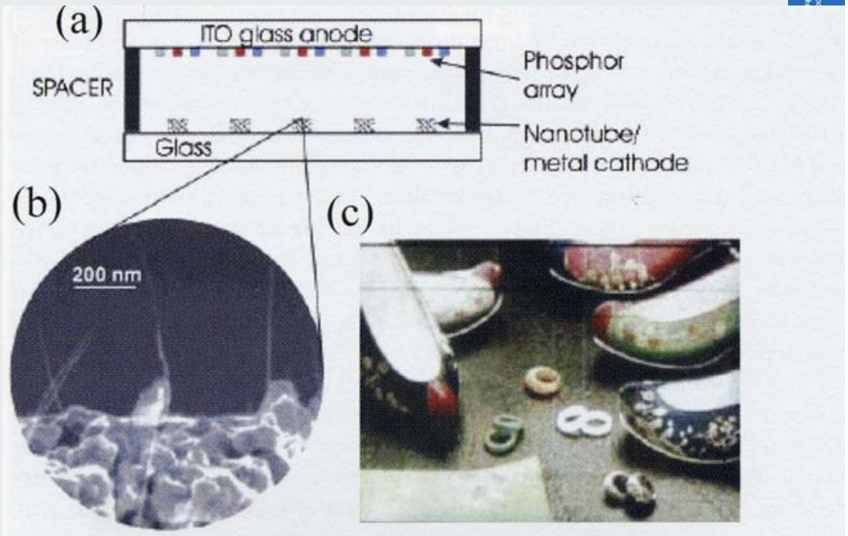
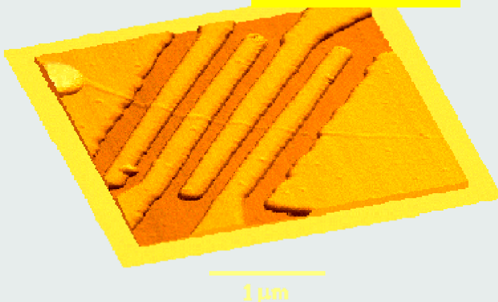


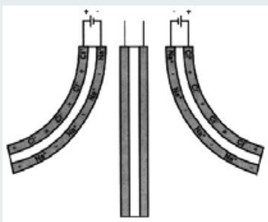
Fig. 8.14. (a) Schematic illustration of a flat panel display based on carbon nanotubes. ITO, indium tin oxide. (b) SEM image of an electron emitter for a display, showing well-separated SWNT bundles protruding from the supporting metal base. (c) Photograph of a 5 in (13 cm) nanotube field emission display made by Samsung. Reproduced from ref. [187], with permission.

(C)NT-Applications

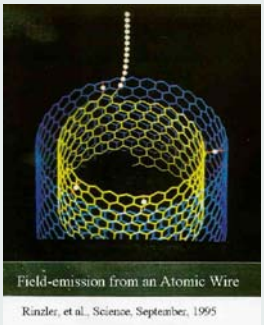
Conductor
rectifyer
transitor
sensor



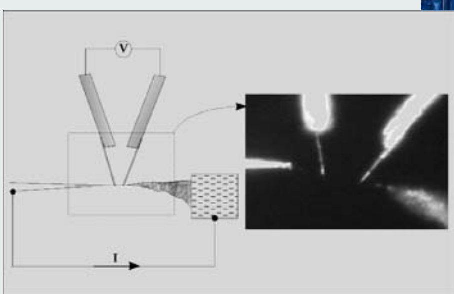
ion sensor
actuator



emission tip



nano tips



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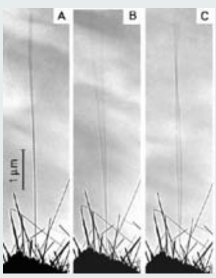
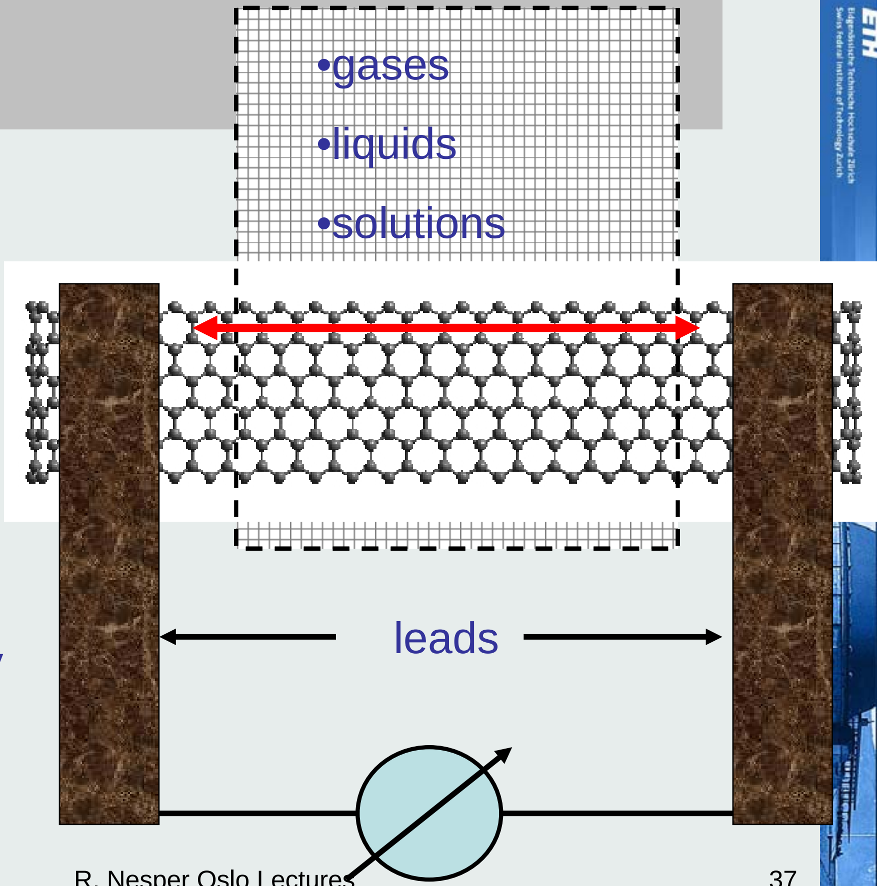


C-NT Sensor

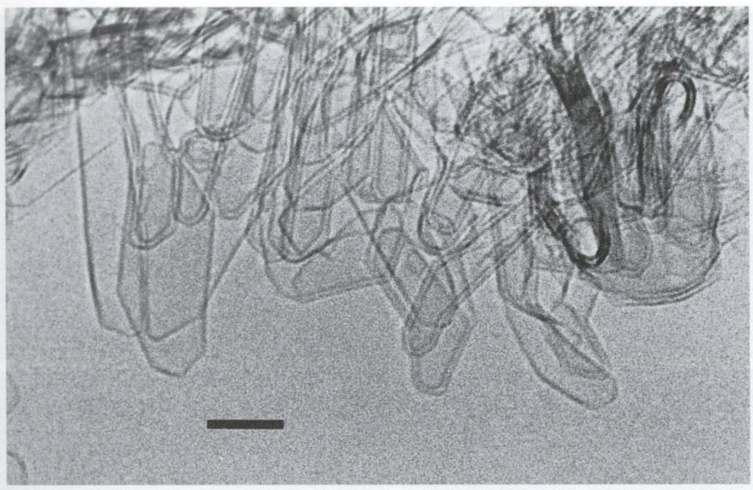
Surface electron conductance

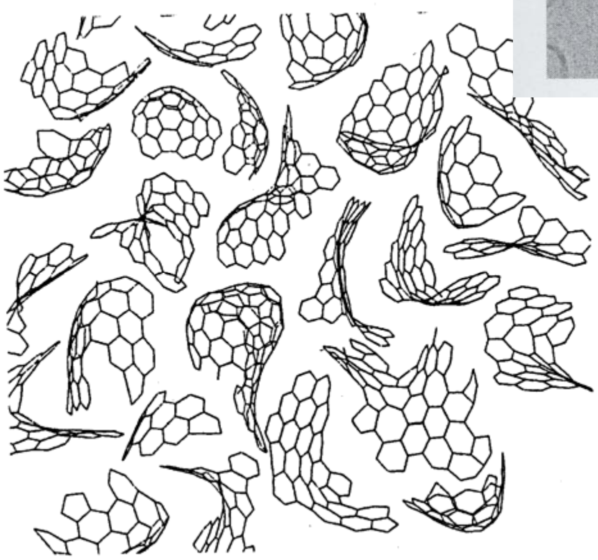


Adsorbed species

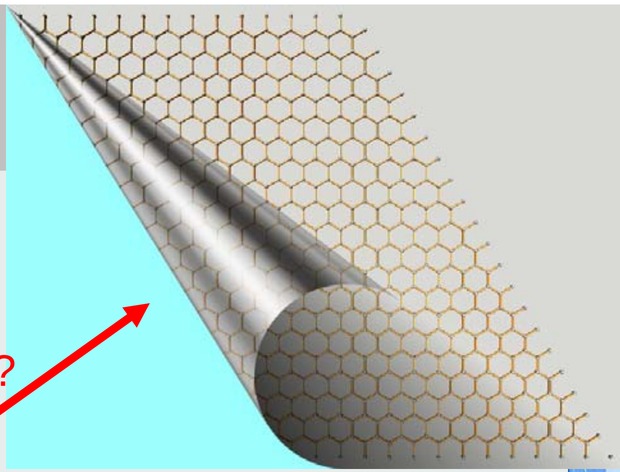
strongly change conductivity

New Carbons ?

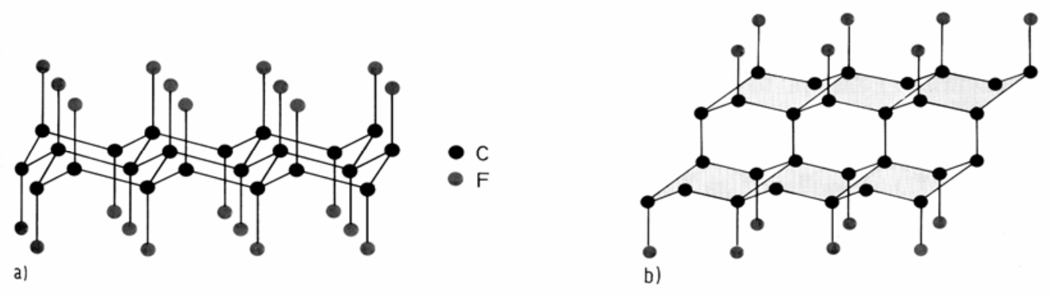




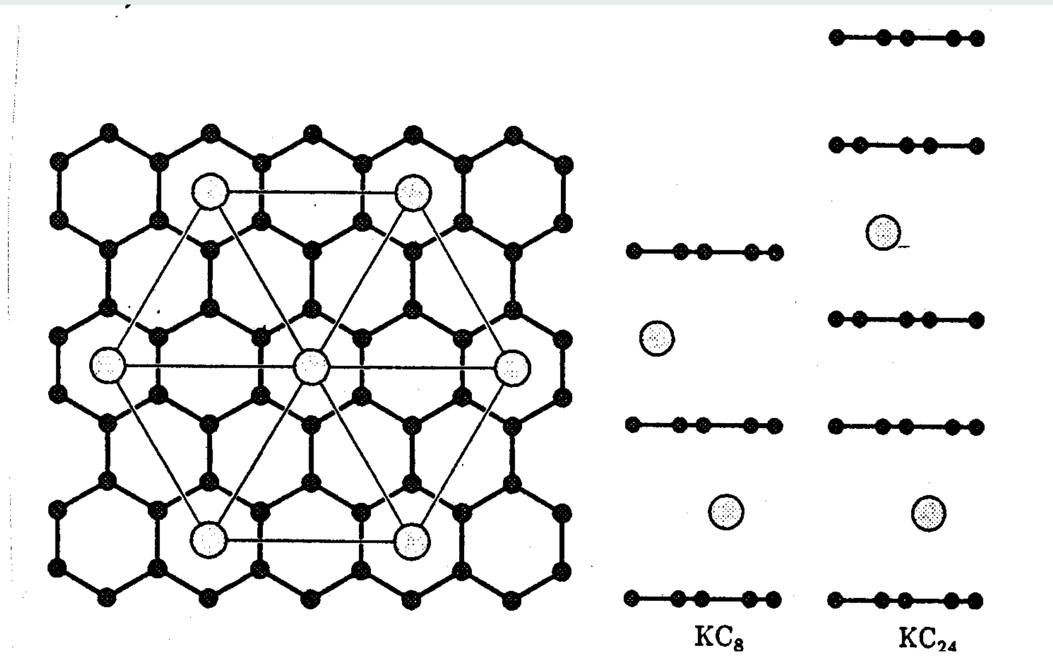
Derivates of Graphite



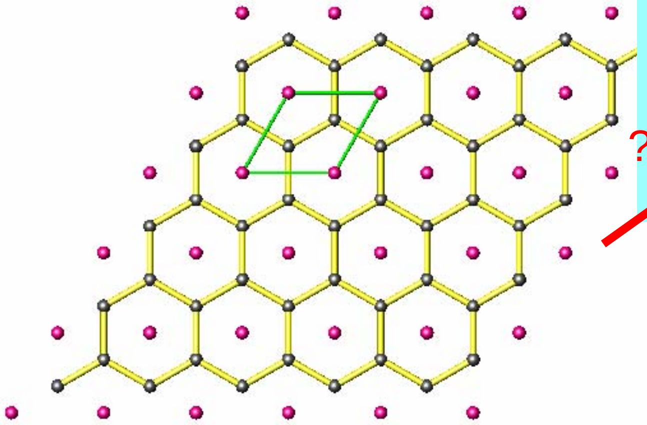
Graphit $\xrightarrow{T = 350 - 600°C}$ $[CF]_x$, x=0.5 - 1

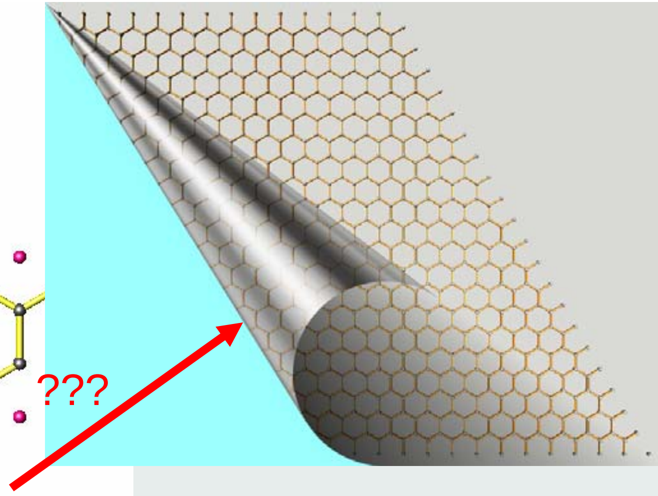


Exfoliate Graphite Intercalation Compounds?



Heterographites





MgB_2
AlB_2
MgB_2C_2
LiBC

Graphite-related Superconductors

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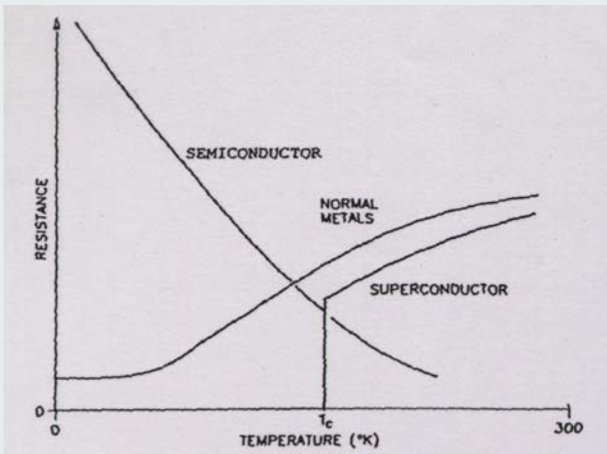
The superconducting materials demonstrate a ***zero electrical resistivity*** in a certain range of temperature, current and magnetic field.

Their maximum values are called:

critical temperature (T_C)

critical current density (J_C)

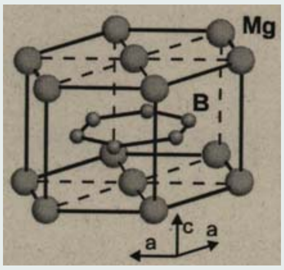
critical magnetic field (H_C)



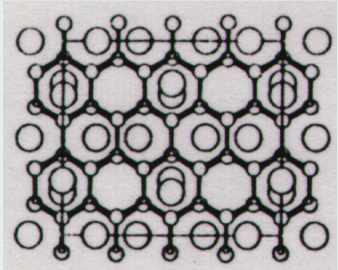
MgB_2
~~MgB_2C_2~~
~~LiBC~~
~~AlB_2~~

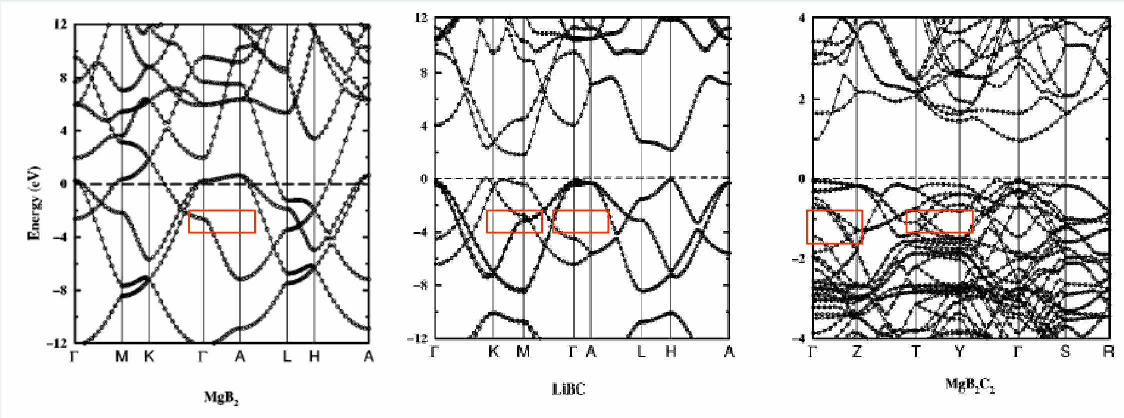
Ca_x-graphite
Yb_x-graphite
~~„$Li_{0.5}BC$“ T_c=90K~~

Supraleitung in MgB_2, LiBC and MgB_2C_2



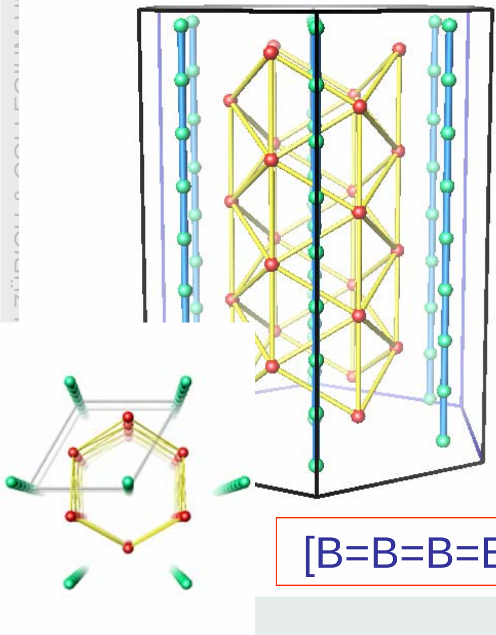
MgB_2
MgB_2C_2
LiBC
$Li_{0.5}BC$ T_c=90K

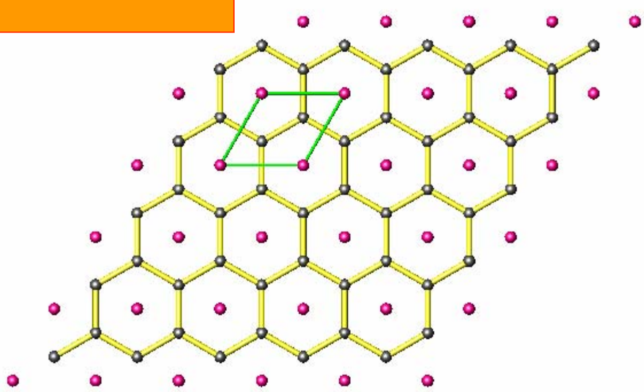




MgB_2 and its Analoga
Wire Preparation ?

LiB —Mg-Melt→ MgB_2





$[B=B=B=B=]_n$

J.M. Reinoso, F. Ottinger, M. Wörle, R. Nesper, *Method for producing a super-conducting material made of MgB_2*, Patent No WO0207149909/2002

Morphologie Preserving Transformation

182 ° C

- molten Litium crystalline Boron

300 ° C

- Li-B liquid solution

450 ° C

- LiB_x formation

550 ° C

- MgB_2 formation

700 ° C

-Under continuous stirring Boron dissolves into molten Lithium, forming an high malleable, low density, metallic solid solution

-The wire is dropped into the crucible just the time to coat it

-The coated wire is placed into the furnace untill the metallic glittering desappears

-The LiB wire is kept into the crucible of molten Magnesium for about 15 min.

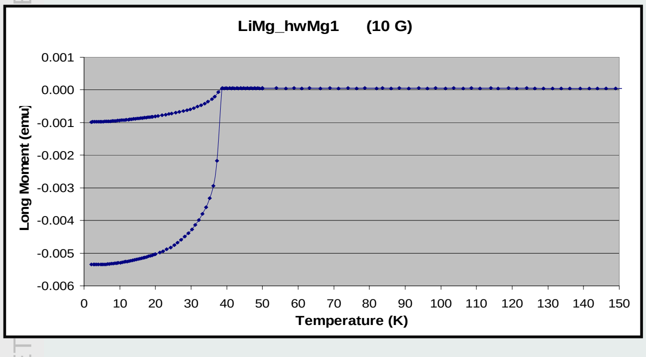
- Sublimation of Mg / Mg_xLi_y under High vacuum, 630 ° C, 8 h

Preparing Wires and Rods

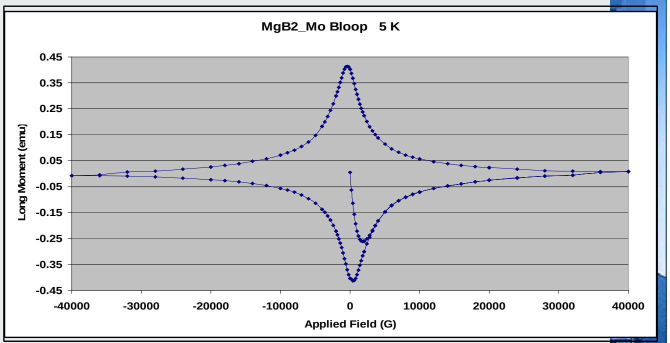
Li-B mixture	LiB_x compound	MgB_2
		
		
- The inner part does not react completely	- The resulting coating is highly porous	- Formation of oxidic layer can occur between the wire and the coating

Magnetische Messungen

reines MgB_2 χ (T)



MgB_2 χ(H)



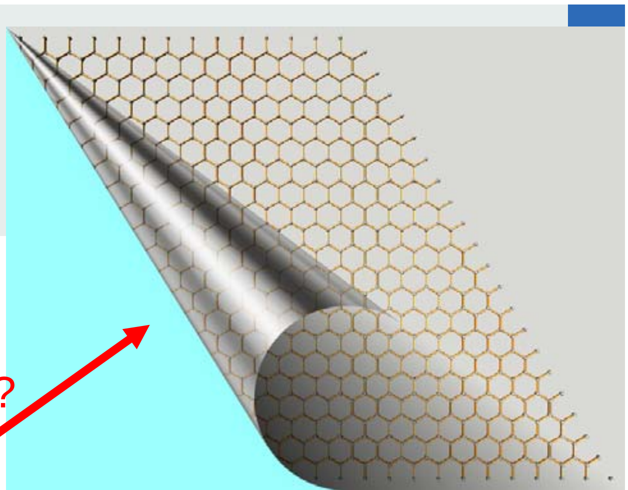
R. NESPER ETH HELVETICUM

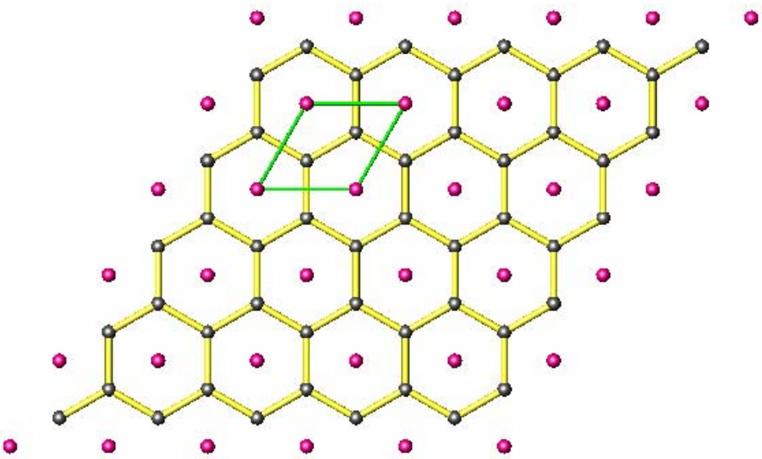
Heterographites –

MgB_2
MgB_2C_2
LiBC

„$Li_{0.5}$BC“ T_c=90K

???





Scrolled Ionic Compounds ?

Chaoite – Substitute ?

$LiB_{0.89}$