Carbon nanotubes.

PH 673

Nanoscience and nanotechnology

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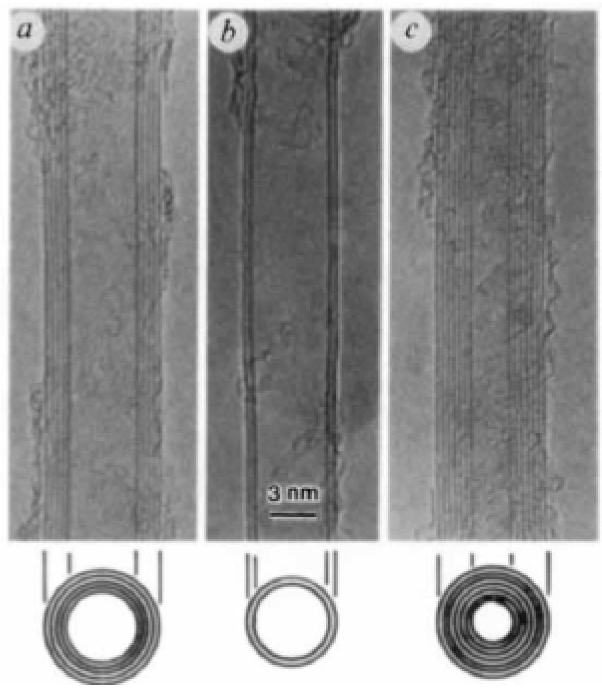
LETTERS TO NATURE

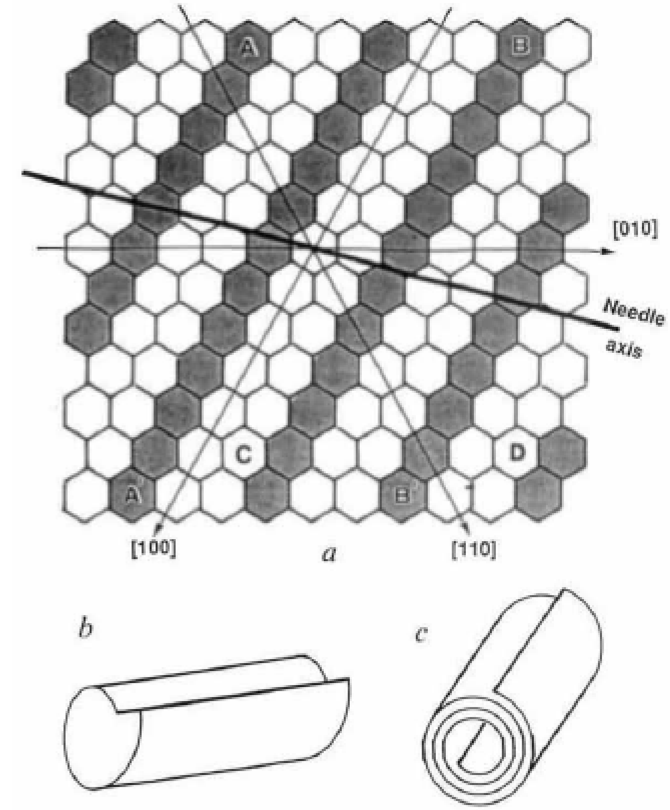
Helical microtubules of graphitic carbon

Sumio Iijima

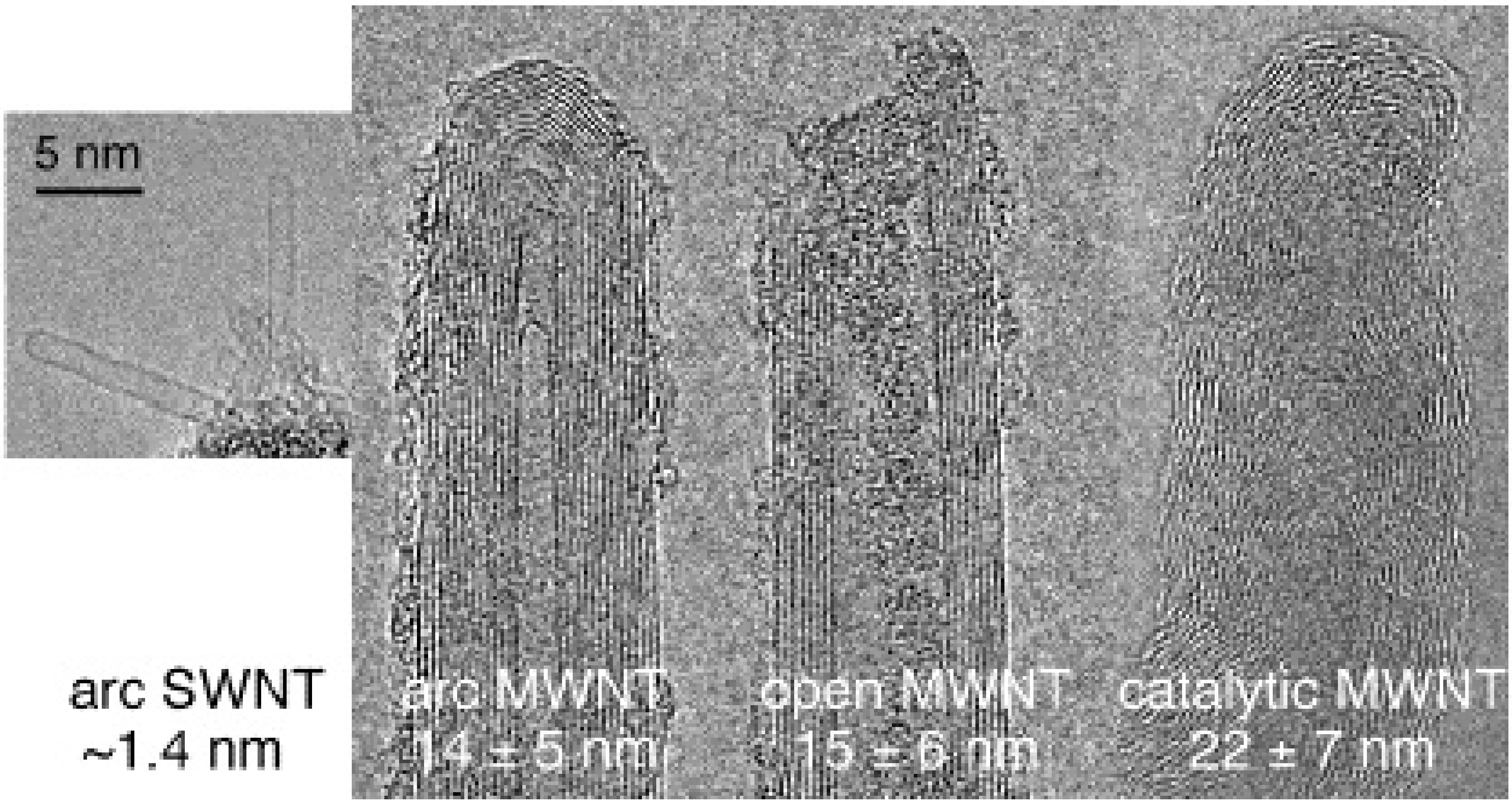
NEC Corporation, Fundamental Research Laboratories,
34 Miyukigaoka, Tsukuba, Ibaraki 305, Japan

NATURE · VOL 354 · 7 NOVEMBER 1991





SWNTs and MWNTs



Carbon nanotubes

Physical Properties of Carbon Nanotubes

Parameter	*Value and units*	*Observations*
Length of the unit vector	$a = \sqrt{3} a_{C-C} = 2.49$ Å	$a_{C-C} = 1.44$ Å is the carbon bond length
Current density	$>10^9$ A/cm^2	-1000 times larger than the current density in copper - Measured in MWCNTs
Thermal conductivity	6600 W/mK	More thermally conductive than most crystals
Young modulus	1 Tpa	Many orders of magnitude stronger than the steel
Mobility	10,000-50,000 cm^{2}V^{-1}s^{-1}	Simulations indicate motilities beyond 100,000 cm^{2}V^{-1}s^{-1}
Mean free path (ballistic transport)	300-700 nm semiconducting CNT 1000-3000 nm metallic CNT	- Measured at room temperature - At least three time larger than the best semiconducting heterostructures
Conductance in ballistic transport	$G = 4e^2 / h = 155 \mu S$; $1/G = 6.5 k\Omega$	
Luttinger parameter g	0.22	The electrons are strongly correlated in CNTs
Orbital magnetic moment	0.7 meVT^{-1} (d = 2.6 nm) 1.5 meVT^{-1} (d = 5 nm)	The orbital magnetic moment depends on the tube diameter

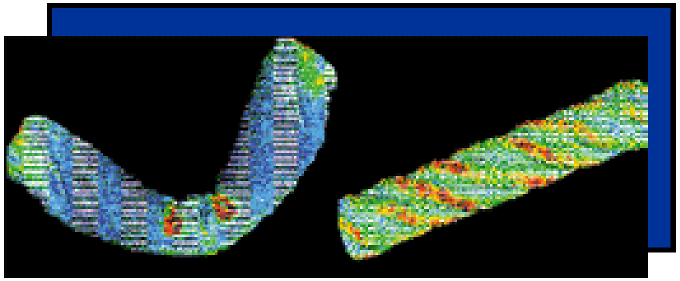
CNT Properties

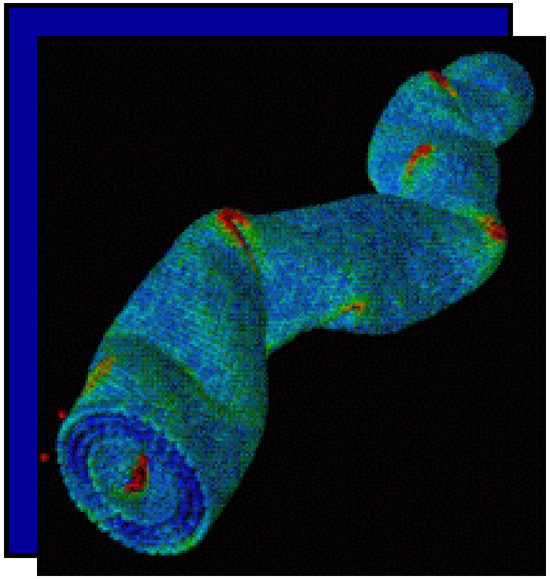
- The strongest and most flexible molecular material because of C-C covalent bonding and seamless hexagonal network architecture

- Young's modulus of over 1 TPa vs 70 GPa for Aluminum, 700 GPA for C-fiber
  - strength to weight ratio 500 time > for Al; similar improvements over steel and titanium; one order of magnitude improvement over graphite/epoxy

- Maximum strain ~10% much higher than any material

- Thermal conductivity ~ 3000 W/mK in the axial direction with small values in the radial direction





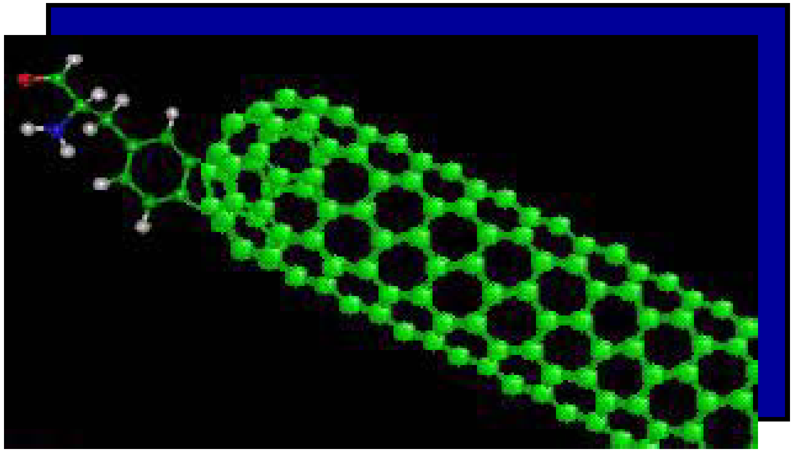
CNT Properties (cont.)

- Electrical conductivity six orders of magnitude higher than copper

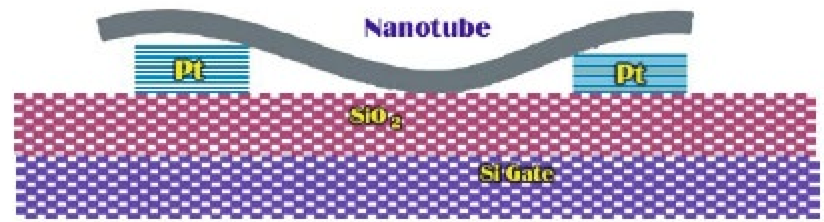
- Can be metallic or semiconducting depending on chirality
    - 'tunable' bandgap
    - electronic properties can be tailored through application of external magnetic field, application of mechanical deformation…

- Very high current carrying capacity

- Excellent field emitter; high aspect ratio and small tip radius of curvature are ideal for field emission

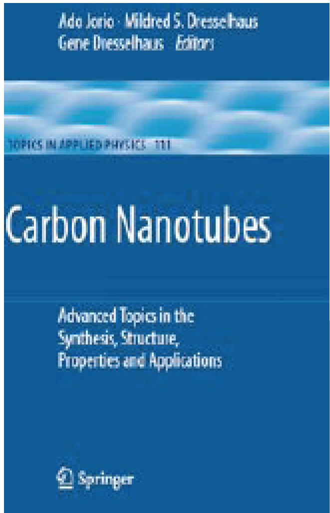


CNT: Implications for electronics



- Carrier transport is 1-D.
- All chemical bonds are

  satisfied $\Rightarrow$ CNT Electronics not bound to use SiO_2 as an insulator.
- High mechanical and thermal stability and resistance to electromigration $\Rightarrow$ Current densities upto 10^9 A/cm^2 can be sustained.
- Diameter controlled by chemistry, not fabrication.
- Both active devices and interconnects can be made from semiconducting and metallic nanotubes.

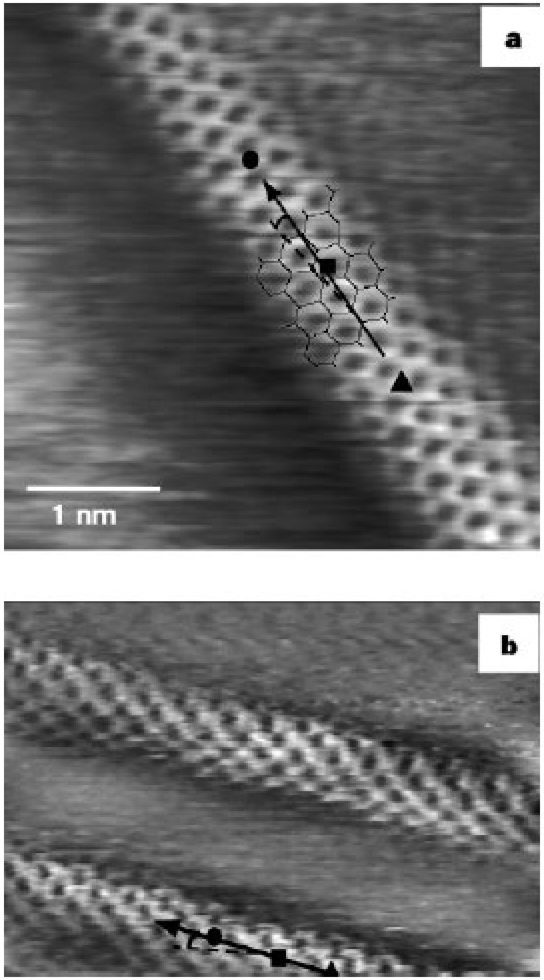


More emphasis now is on applications

Potential Applications of Carbon Nanotubes

Chapter by M. Endo, M. S. Strano, P. M. Ajayan @ Springer TAP111

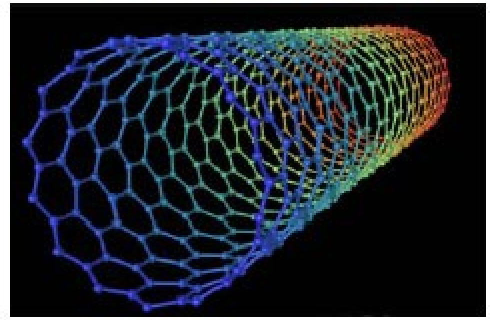
	Large Volume Applications	**Limited Volume Applications (Mostly based on Engineered Nanotube Structures)**
Present	- Battery Electrode Additives (MWNT) - Composites (sporting goods; MWNT) -Composites (ESD* applications; MWNT) -(*ESD – Electrical Shielding Device)	- Scanning Probe Tips (MWNT) - Specialized Medical Appliances (catheters) (MWNT)
Near Term (less than ten years)	- Battery and Super-capacitor Electrodes - Multifunctional Composites - Fuel Cell Electrodes (catalyst support) - Transparent Conducting Films - Field Emission Displays / Lighting - CNT based Inks for Printing	- Single Tip Electron Guns - Multi-Tip Array X-ray Sources - Probe Array Test Systems - CNT Brush Contacts - CNT Sensor Devices - Electro-mechanical Memory Device - Thermal Management Systems
Long Term (beyond ten years)	- Power Transmission Cables - Structural Composites (aerospace and automobile etc.) - CNTs in Photovoltaic Devices	- Nano-electronics (FET,Interconnects) - Flexible Electronics - CNT based bio-sensors - CNT Fitration/Separation Membranes - Drug-delivery Systems



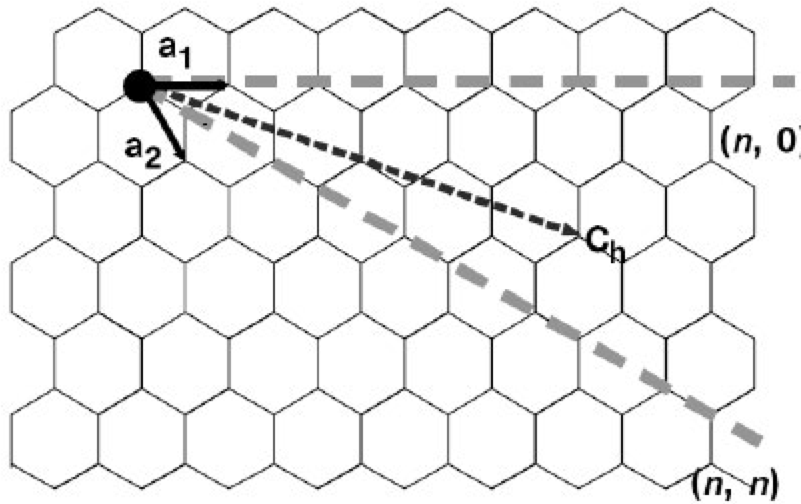
STM images of carbon nanotubes
T.W. Odom, J.-L. Huang, P.Kim, C.Lieber, Nature 391 (1998)

Carbon nanotubes

Iijima 1991
Smalley 1993



$$\Theta = \tan^{-1}\left[\frac{\sqrt{3}n}{2m+n}\right]$$



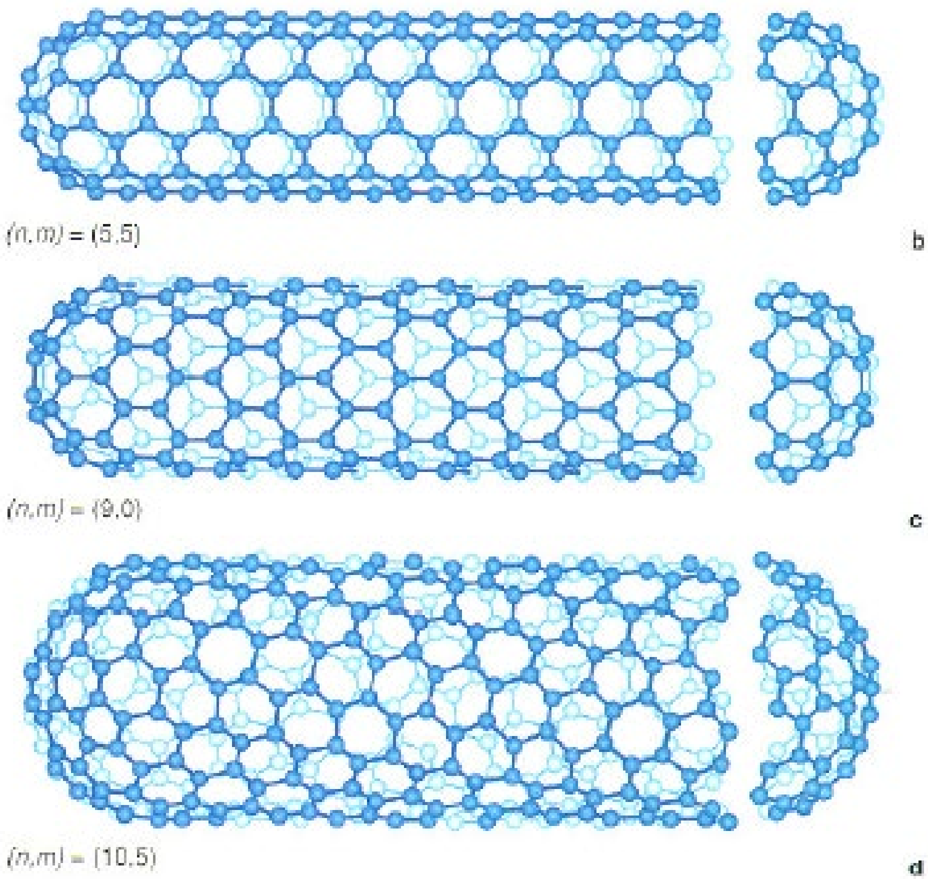
Chiral vector
$C_h = n\mathbf{a_1} + m\mathbf{a_2}$

1.42 Å

$a_0 \sqrt{3}/\pi$

CNT diameter:
$d = (n^2 + m^2 + nm)^{1/2}\ 0.0783\ nm$

Types of carbon nanotubes

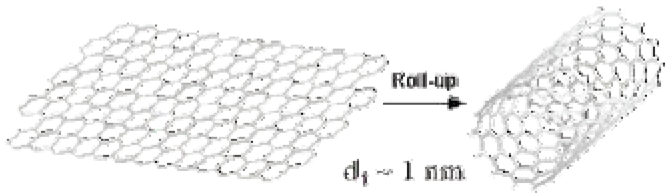


Armchair (n,m) = (5,5)
$\theta = 30°$

Zig Zag (n,m) = (9,0)
$\theta = 0°$

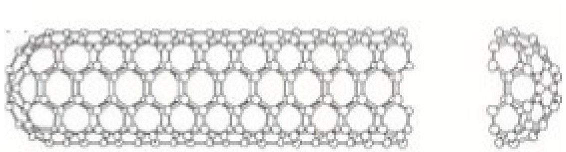
Chiral (n,m) = (10,5)
$0° < \theta < 30°$

Unique Properties of Carbon Nanotubes within the Nanoworld

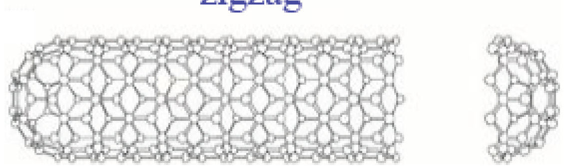


graphene ribbon **SWNT**

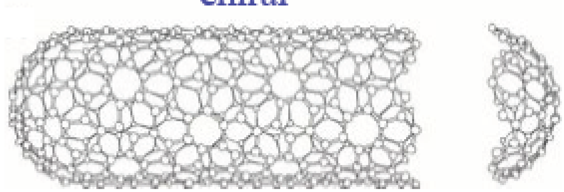
armchair



zigzag



chiral



• Small size: ~1 nm diameter (down to ~10 atoms around the circumference)

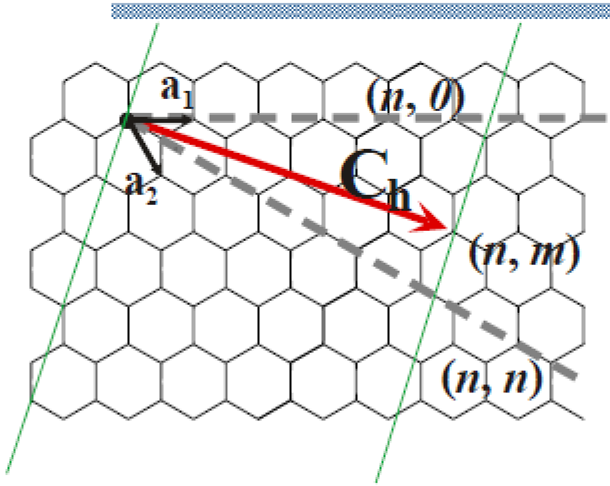
• Electronic Properties: can be either metallic or semiconducting depending on diameter and orientation of the hexagons

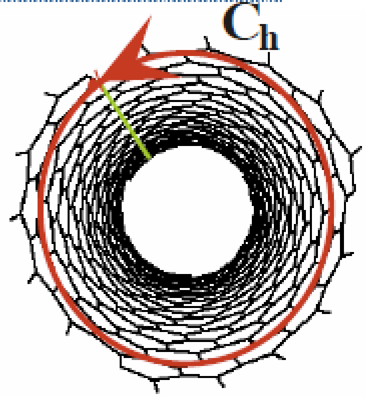
• Mechanical: Very high strength, modulus, and resiliency.

• Physics: model system for1D density of electronic states.

• Single molecule Raman spectroscopy, luminescence and transport properties.

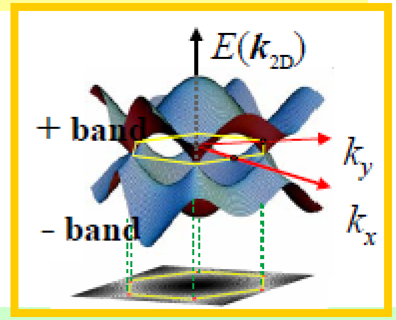
Rolling Up Graphene: Periodic Boundary Condition

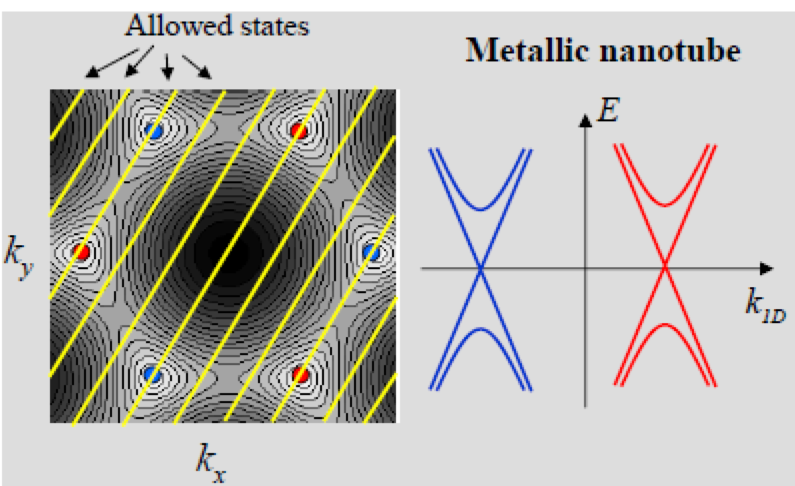


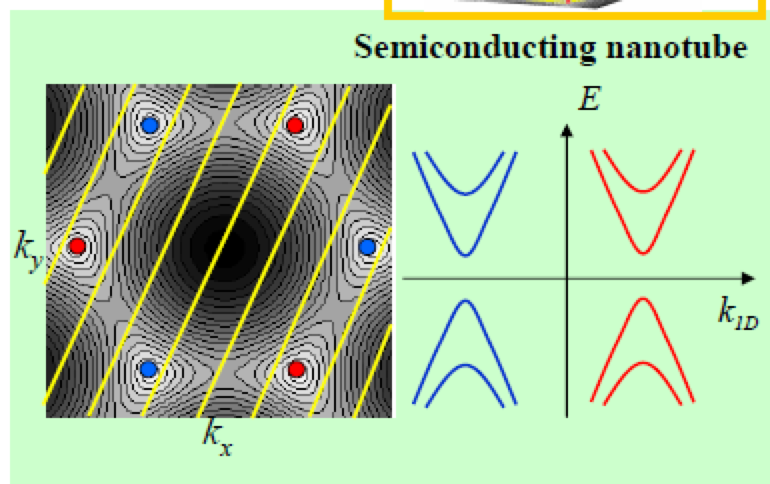


Periodic Boundary Condition

$$C_h \cdot \vec{k}_\perp = 2\pi q$$

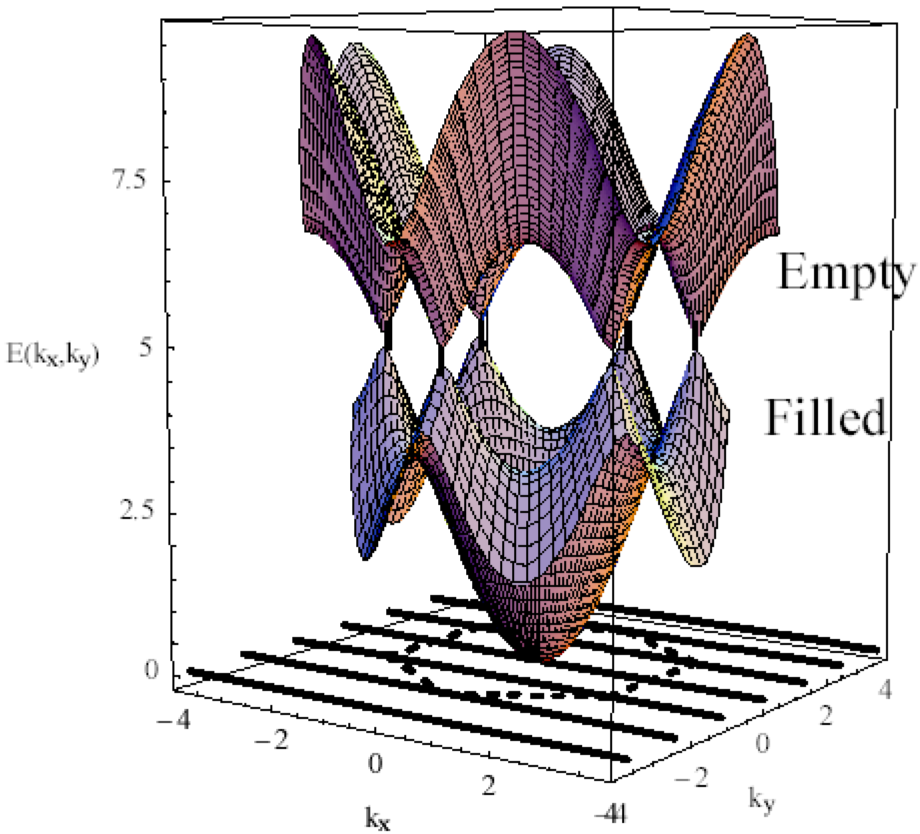


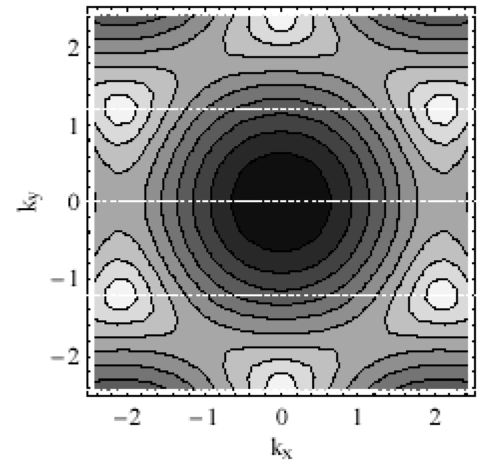


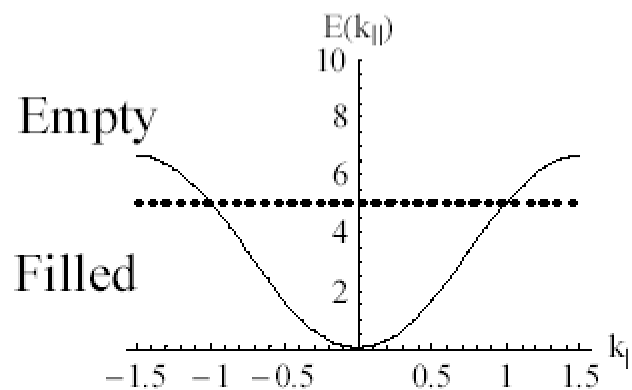


Nanotube: Metallic

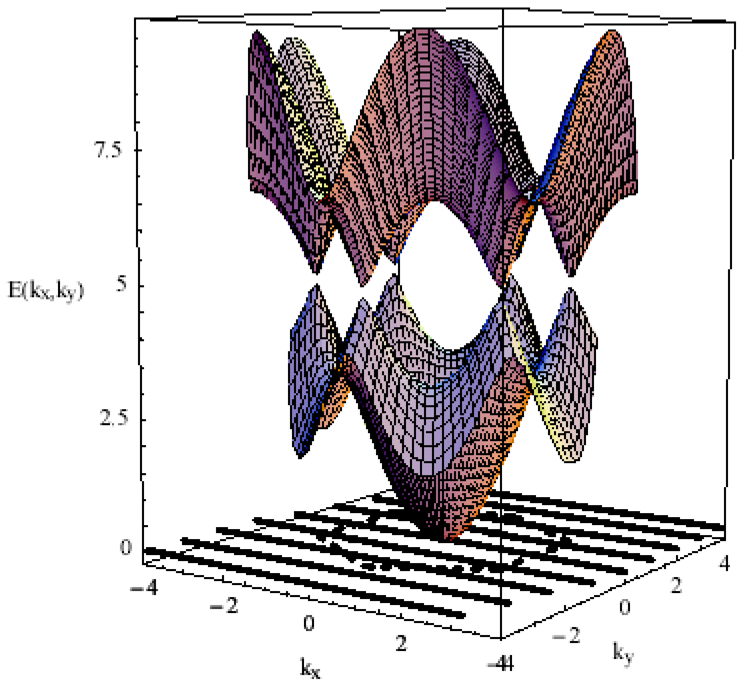
Mads Brandbyge, MIC 2003

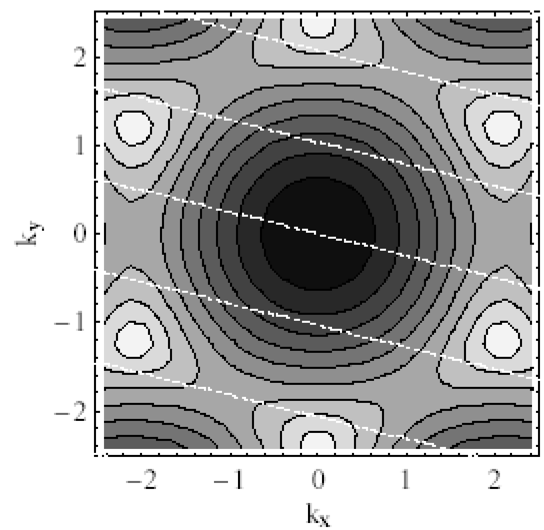


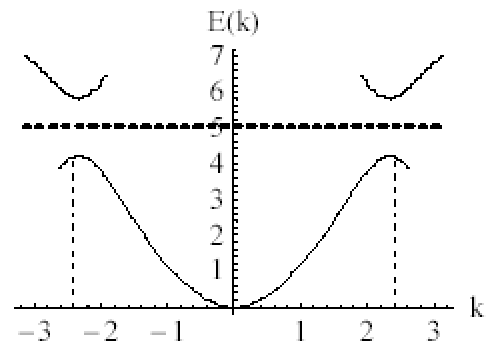




Nanotube: Semi-conductor

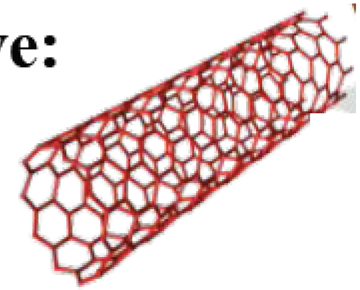




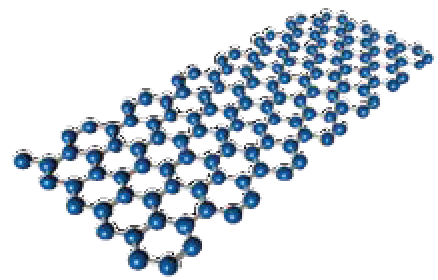


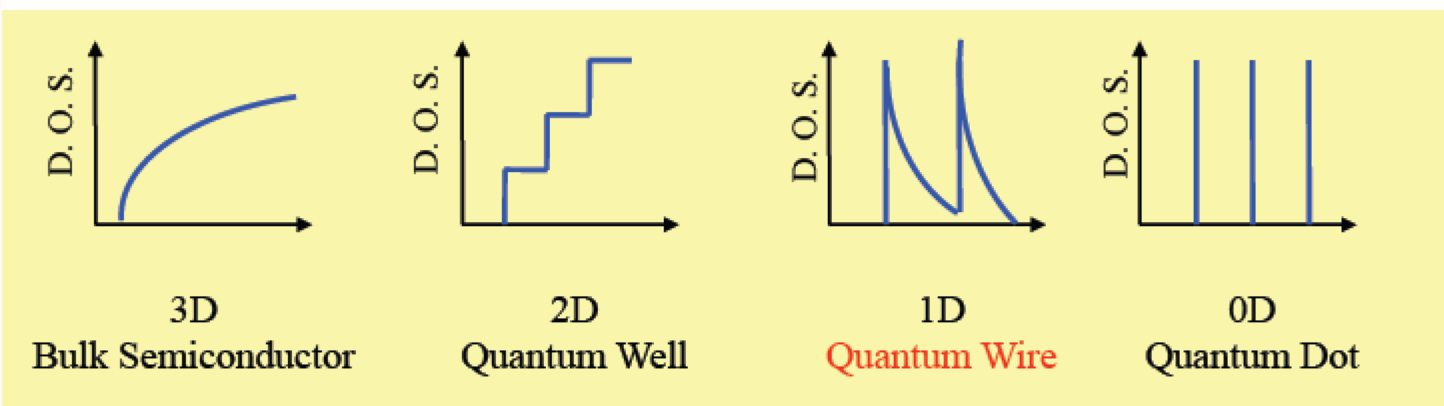
Unique One Dimensional (1D) Properties

Carbon nanotubes and nanoribbons have:



- **High aspect ratio**
- **Enhanced density of states in 1D**
- **Molecular behavior (spikes in DOS)**
- **Solid state behavior (tails in DOS)**





Appl. Phys. Lett. 60 (18), 4 May 1992

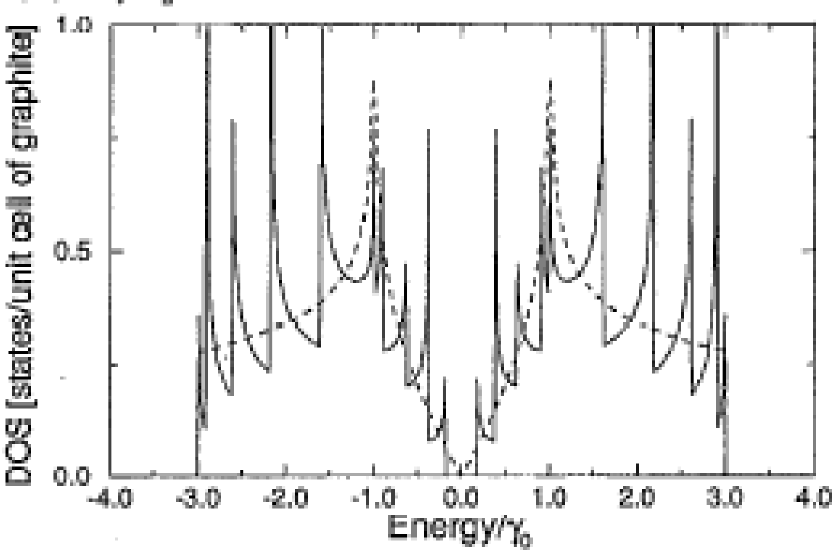
Electronic structure of chiral graphene tubules

R. Saito, M. Fujita, G. Dresselhaus, and M. S Dresselhaus
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 27 January 1992; accepted for publication 4 March 1992)

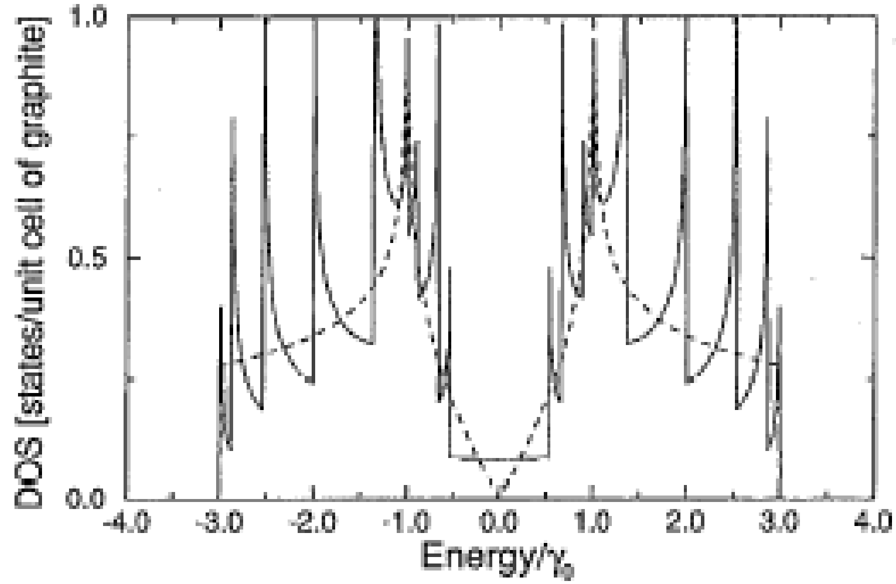
semiconducting

(a) $(n_1,n_2)=(10,0)$



metallic

(b) $(n_1,n_2)=(9,0)$

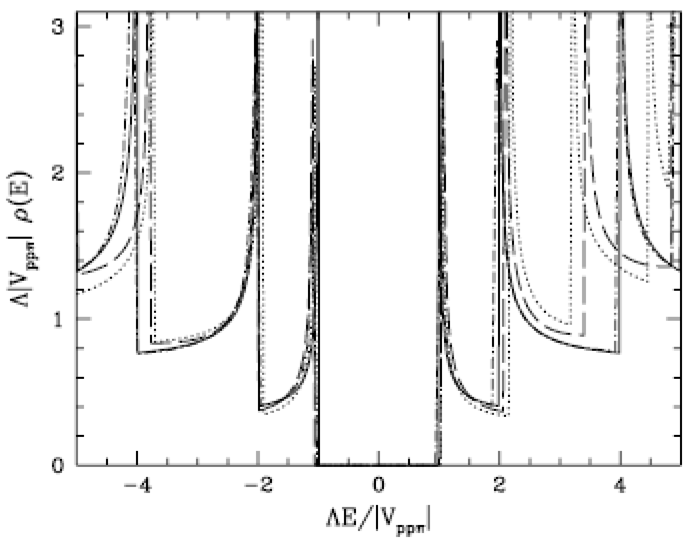


Dashed line: graphene
Note: linear density of states at around zero in graphene – different from either metallic or semiconducting nanotubes !!

Universal Density of States for Carbon Nanotubes

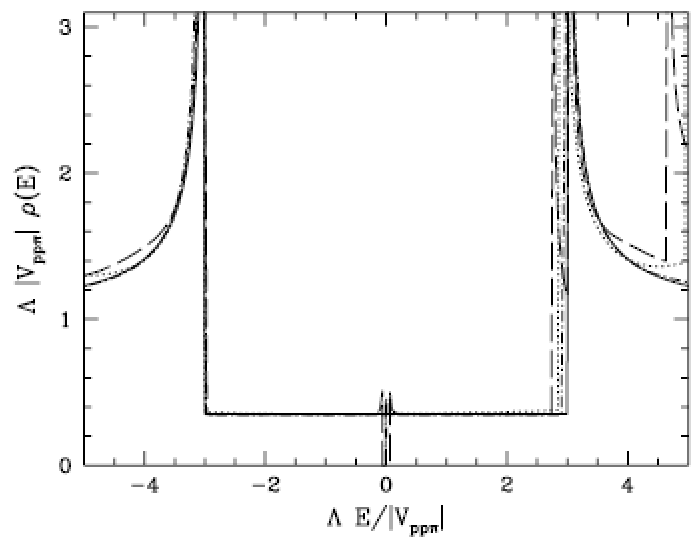
J. W. Mintmire and C. T. White
Code 6179, U.S. Naval Research Laboratory, Washington, D.C. 20375-5342
(Received 13 March 1998)

Semiconducting



(16,0); (13,6); (21,20)

Metallic

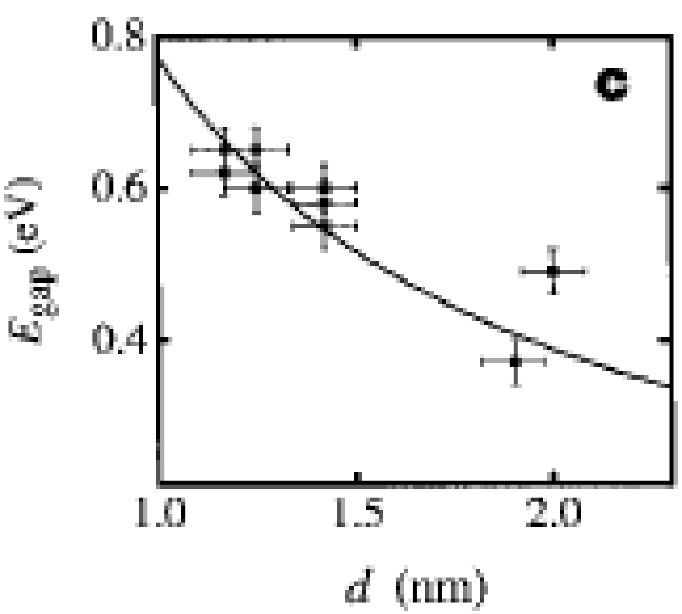


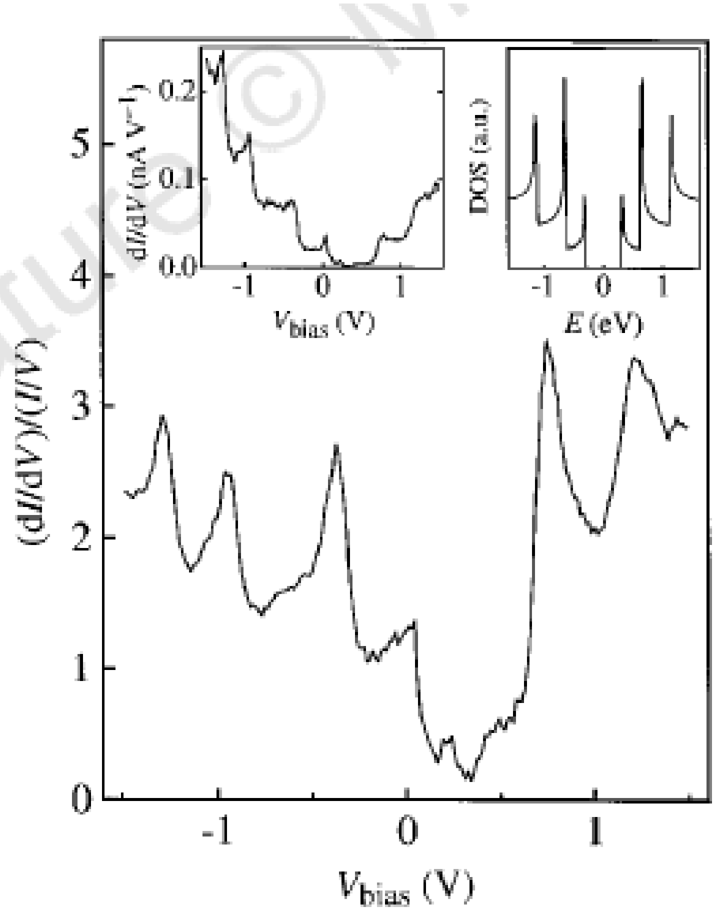
(10,10); (14,5); (22,19)

NATURE | VOL 391 | 1 JANUARY 1998

Electronic structure of atomically resolved carbon nanotubes

Jeroen W. G. Wildöer*, Liesbeth C. Venema*, Andrew G. Rinzler†, Richard E. Smalley† & Cees Dekker*

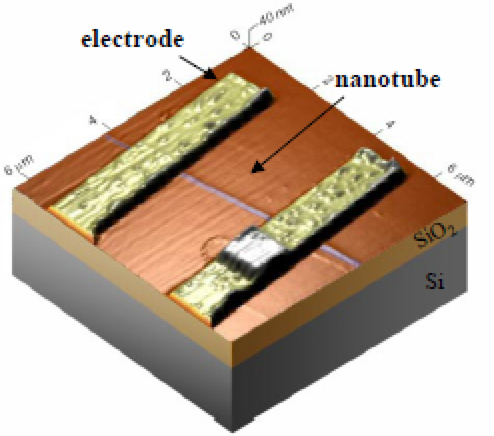


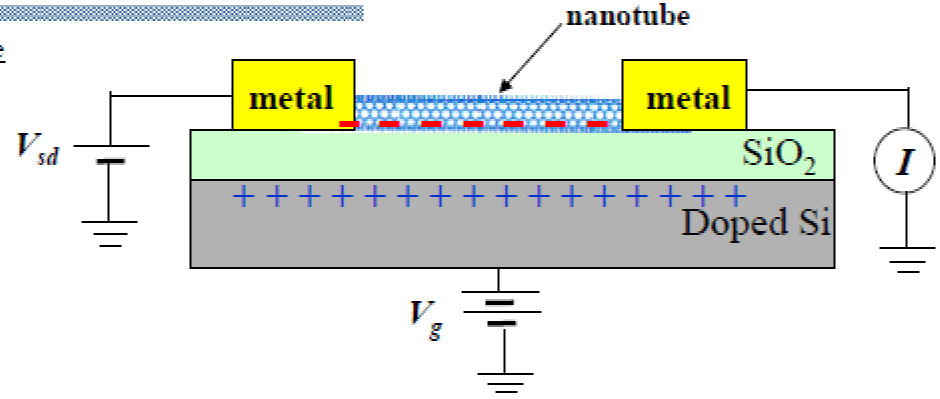


Use STM to probe DOS: shifts and broadening due to hybridization of CNT wave functions with Au substrate

Tuning Carrier Density by Electric Field Effect

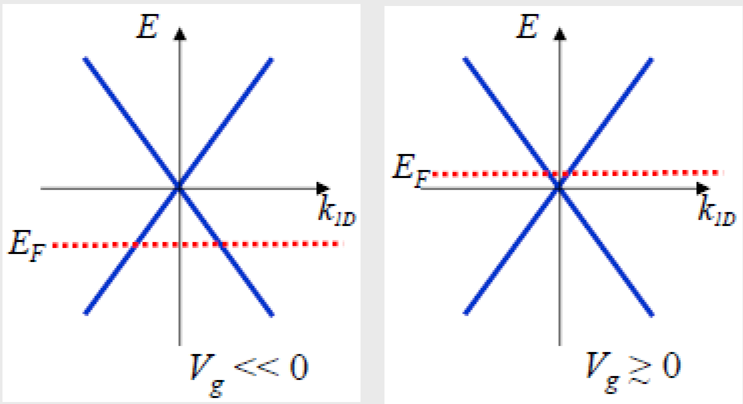
Atomic force microscope image of nanotube device



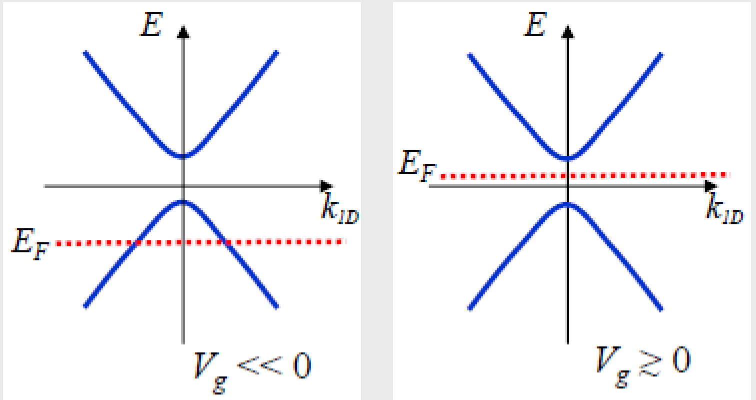


Induced charge: $C_g V_g = e\, n = e\,(\text{D.O.S})\, \Delta E_F$

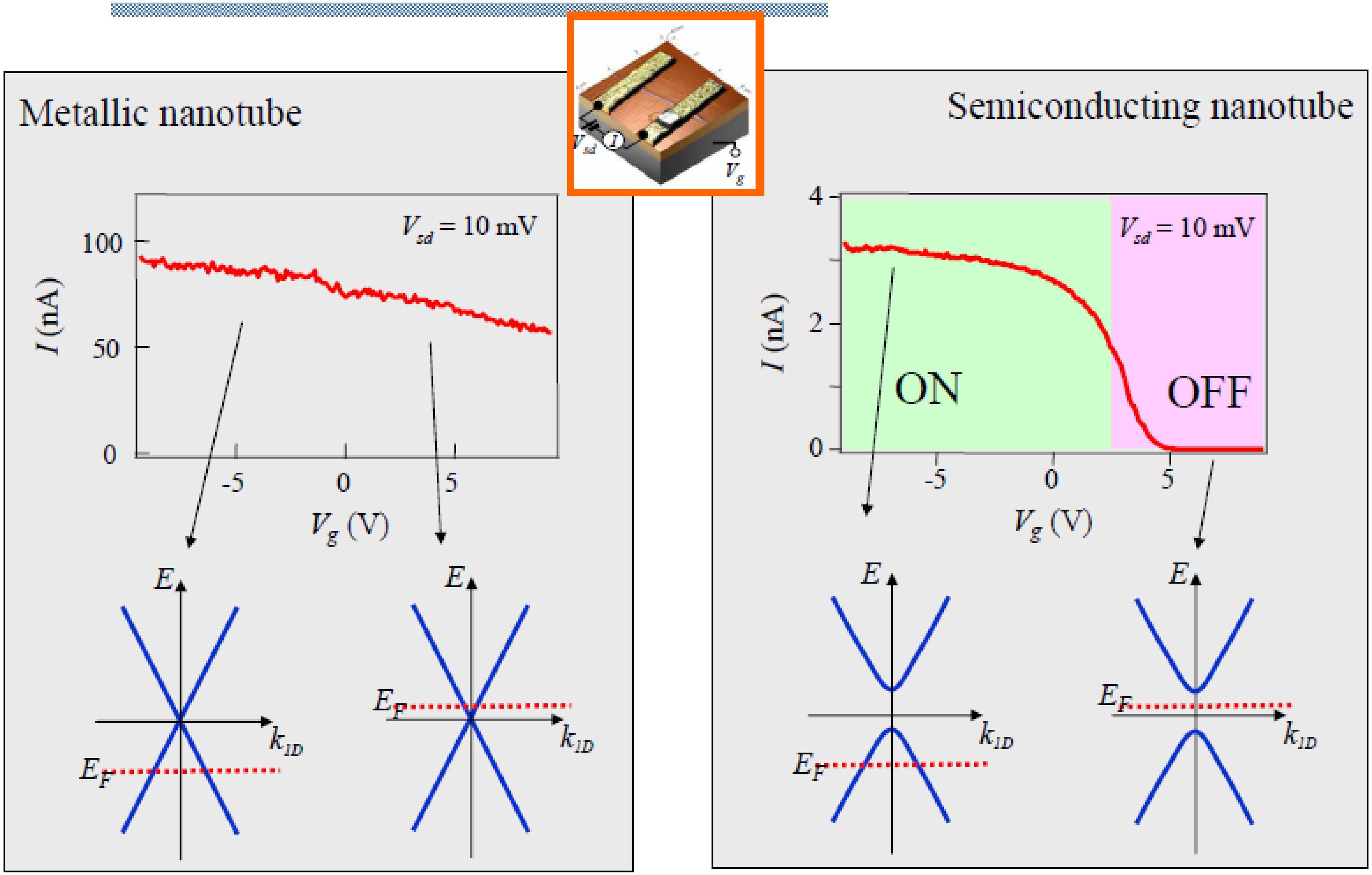
Metallic nanotube



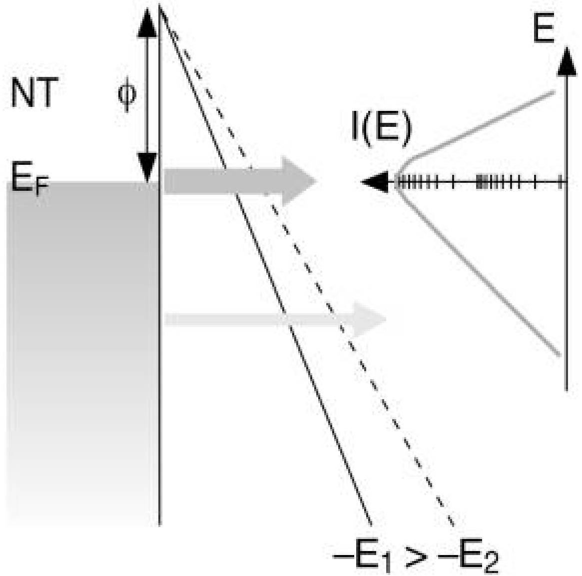
Semiconducting nanotube



Electrical Transport in Nanotube Devices



Field emission: CNTs are much better than metals



Fowler-Nordheim

$$I = aV^2 \exp\left(-\frac{b\phi^{1.5}}{\beta V}\right)$$

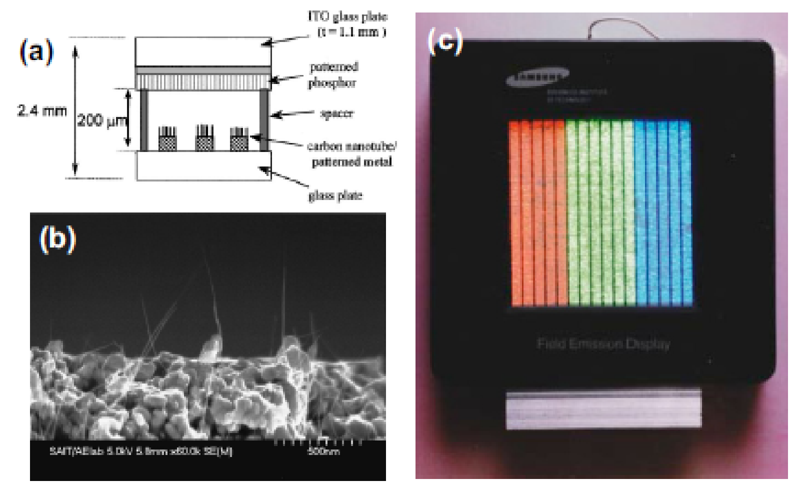
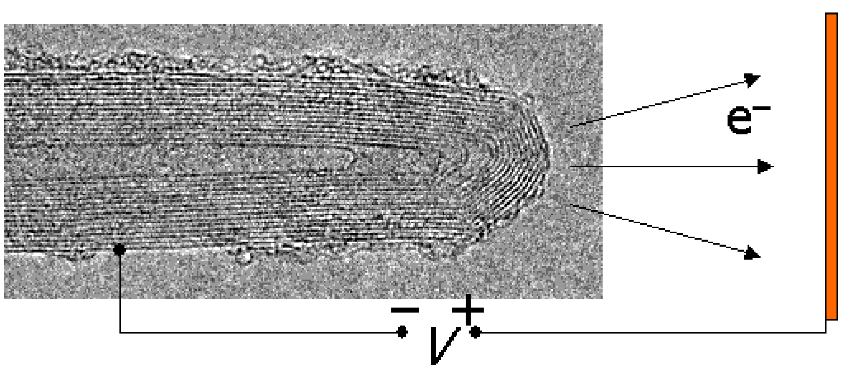


Figure 57. (*a*) Picture representing the set-up of a field emission display. CNTs are deposited on a patterned metal substrate. Field emitted electrons hit the phosphor screen and cause light emission in a colour that depends on the chemical compound on the phosphor screen. (*b*) SEM image of nanotube bundles projecting from the metal electrode. (*c*) A sealed CNT field emission display emitting light in three different colours. The dimension of the display is 4.5 in. From [Cho99a].



CNT-based compact low-power X-ray sources

Issues

Large range of production techniques:

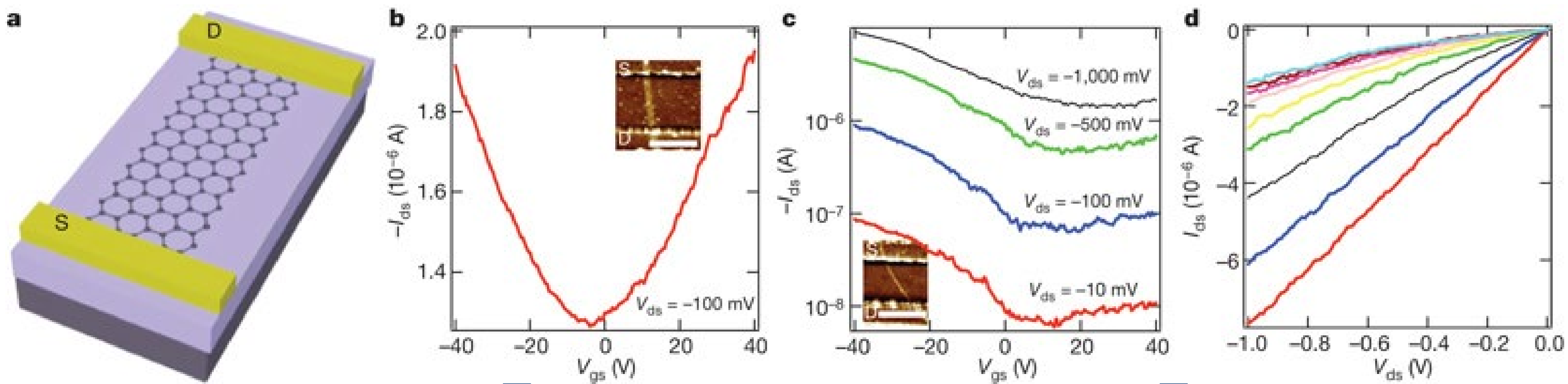
- Carbon arc discharge
- Laser vaporization or ablation
- Chemical vapour deposition
- Electrolysis

Remaining challenges:

- Chemical modification
- Functionalization
- Soluabilization
- Separation into specific (n,m)
- Filling
- Doping
- Manipulation of individual tubes

Grobert, *Materials Today* **10**, 28 (2007)

Room-temperature electrical properties of GNR devices.



16 nm width – like graphene

7 nm width – p-type semiconductor

The all-semiconducting nature of sub-10-nm GNRs could bypass the problem of the extreme chirality dependence of the metal or semiconductor nature of carbon nanotubes (CNTs) in future electronics

LY Jiao *et al. Nature* **458**, 877-880 (2009) doi:10.1038/nature07919

nature