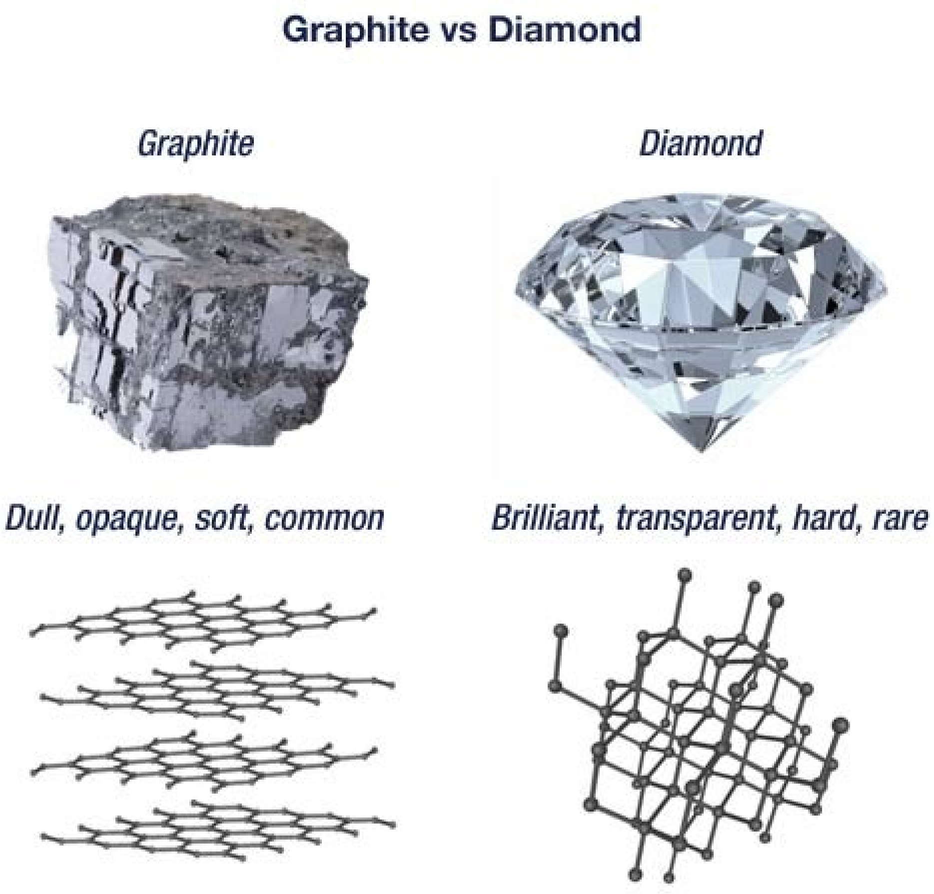
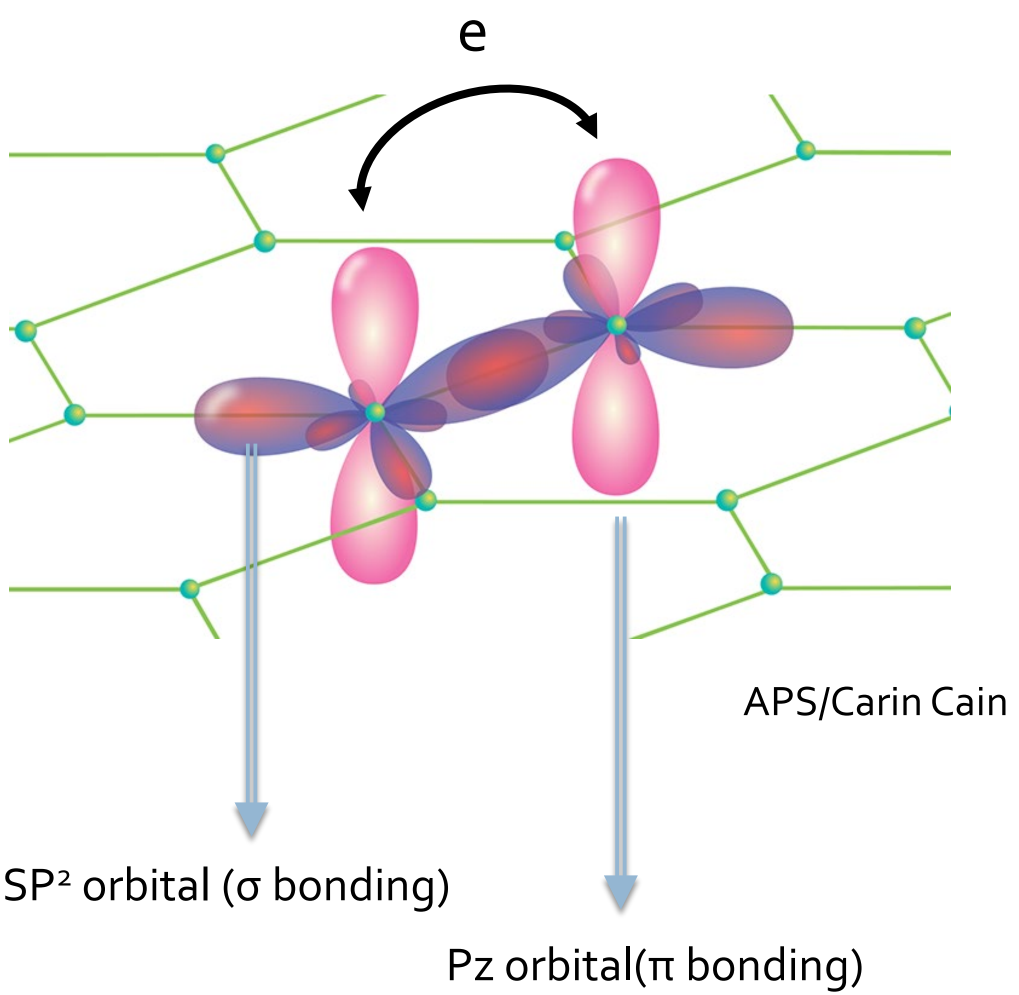
CARBON-BASED NANOMATERIALS

Chung-Ting Ke

03/5/25

Carbon


Graphite vs Diamond
Graphite
Diamond
Dull, opaque, soft, common
Brilliant, transparent, hard, rare


e
APS/Carin Cain
SP² orbital (σ bonding)
Pz orbital(π bonding)

Carbon materials

Simply arrange carbon differently, you will obtain very different outcomes:

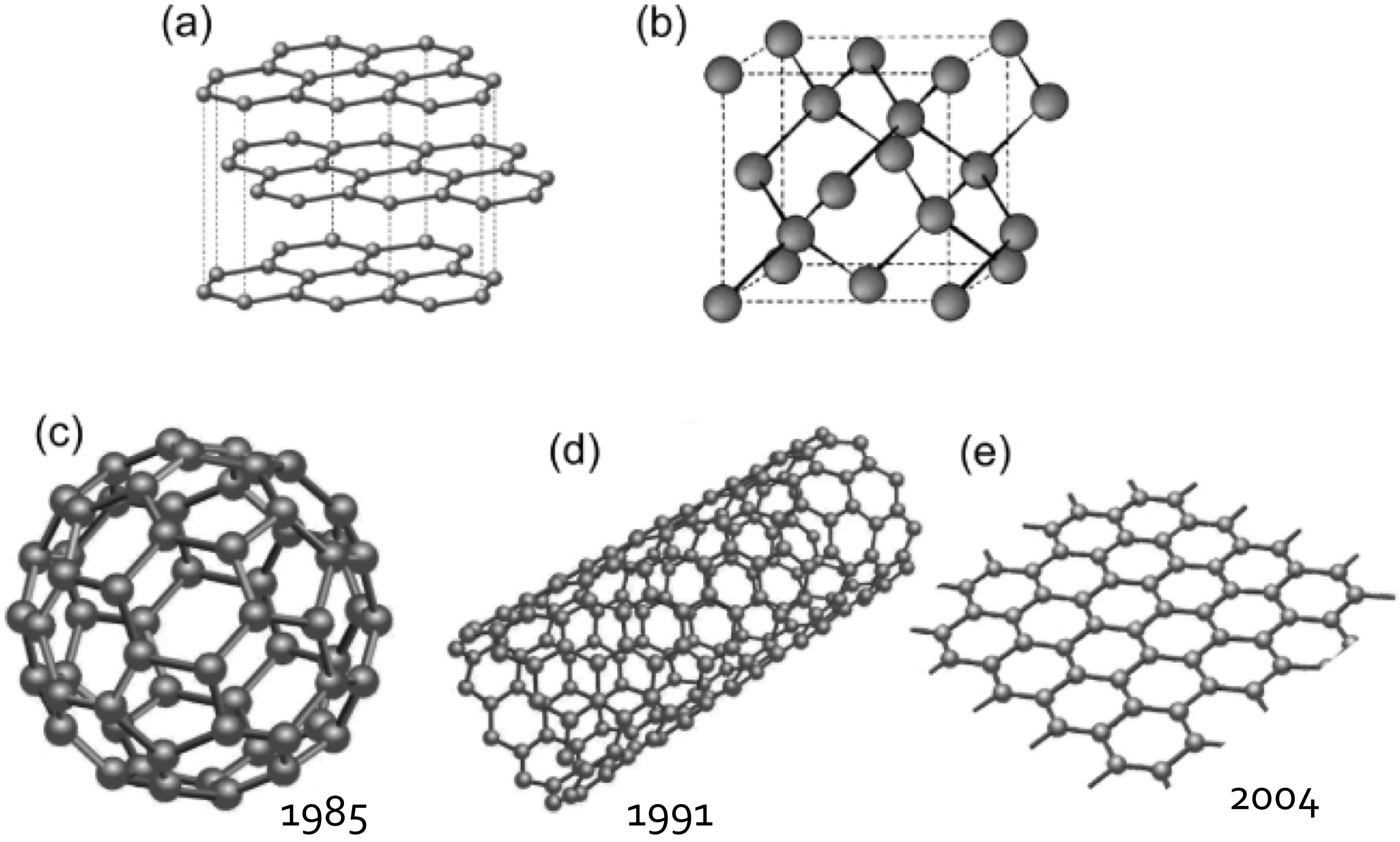
(a) Graphite

(b) Diamond

(c) Buckminster C_{60}

(d) Carbon nanotube

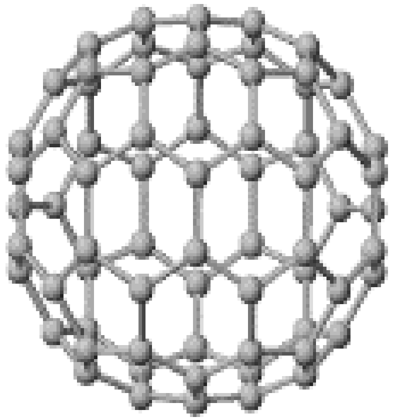
(e) Graphene



M. Scarselli et al. J. Phys. Condes. Matter (2012)

Fullerene

C70



Nobel prize 1996

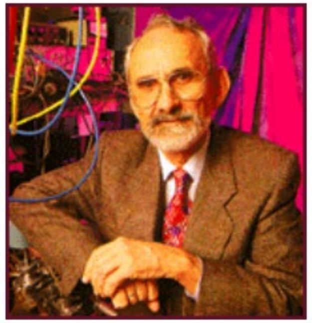


Photo: P. S. Howell, Rice University

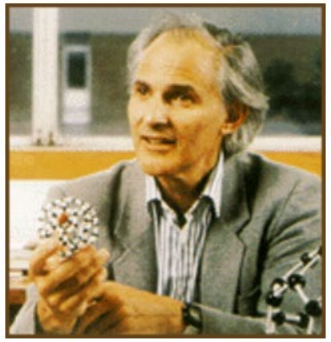
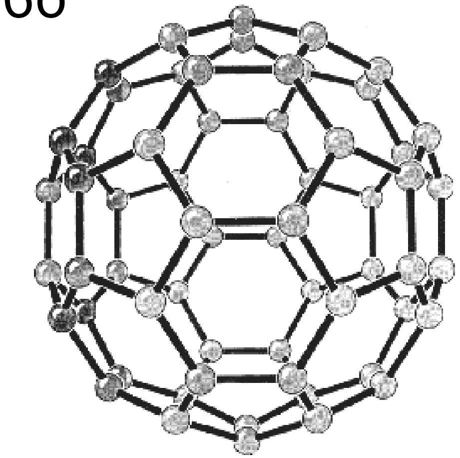


Photo: Prudence Cummings Associates

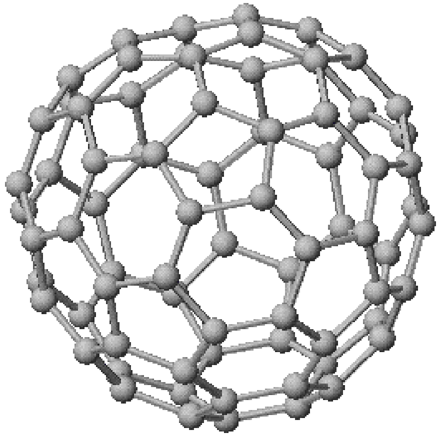
Photo: P. S. Howell, Rice University

C60



Models of the structures of C_{60}. (Acc. Chem. Res., Vol. 25, No. 3, 1992)

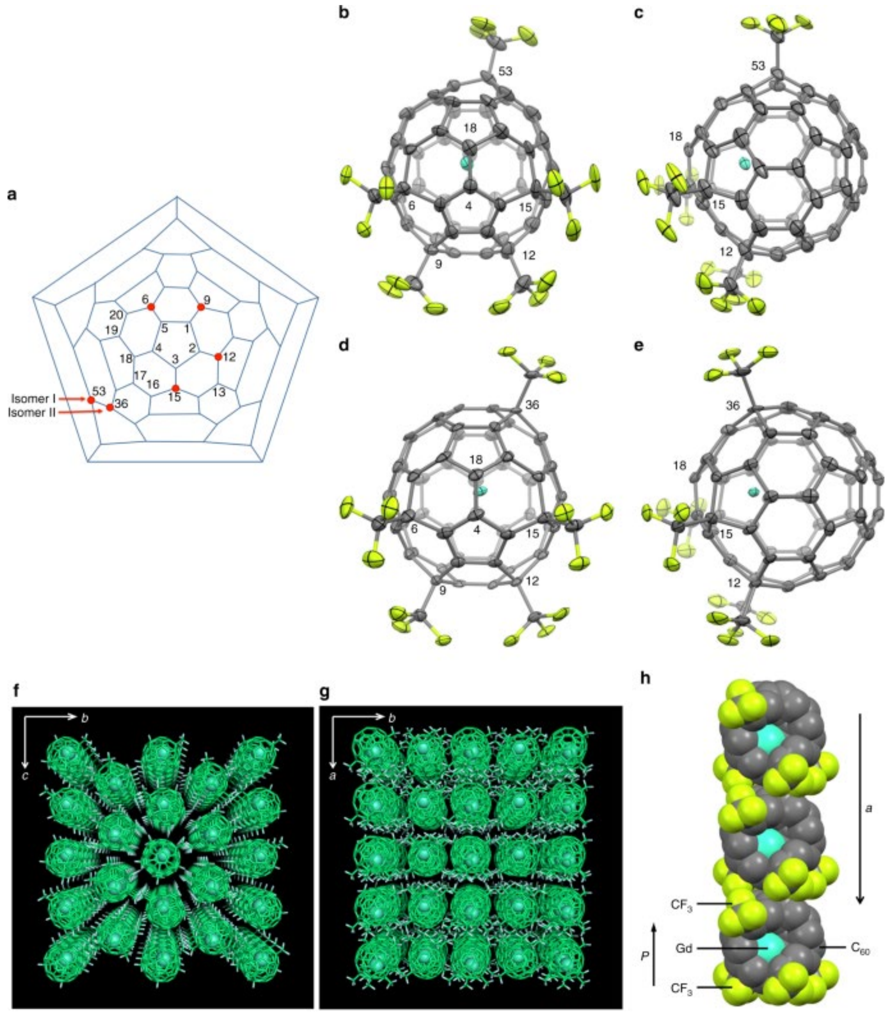
C76



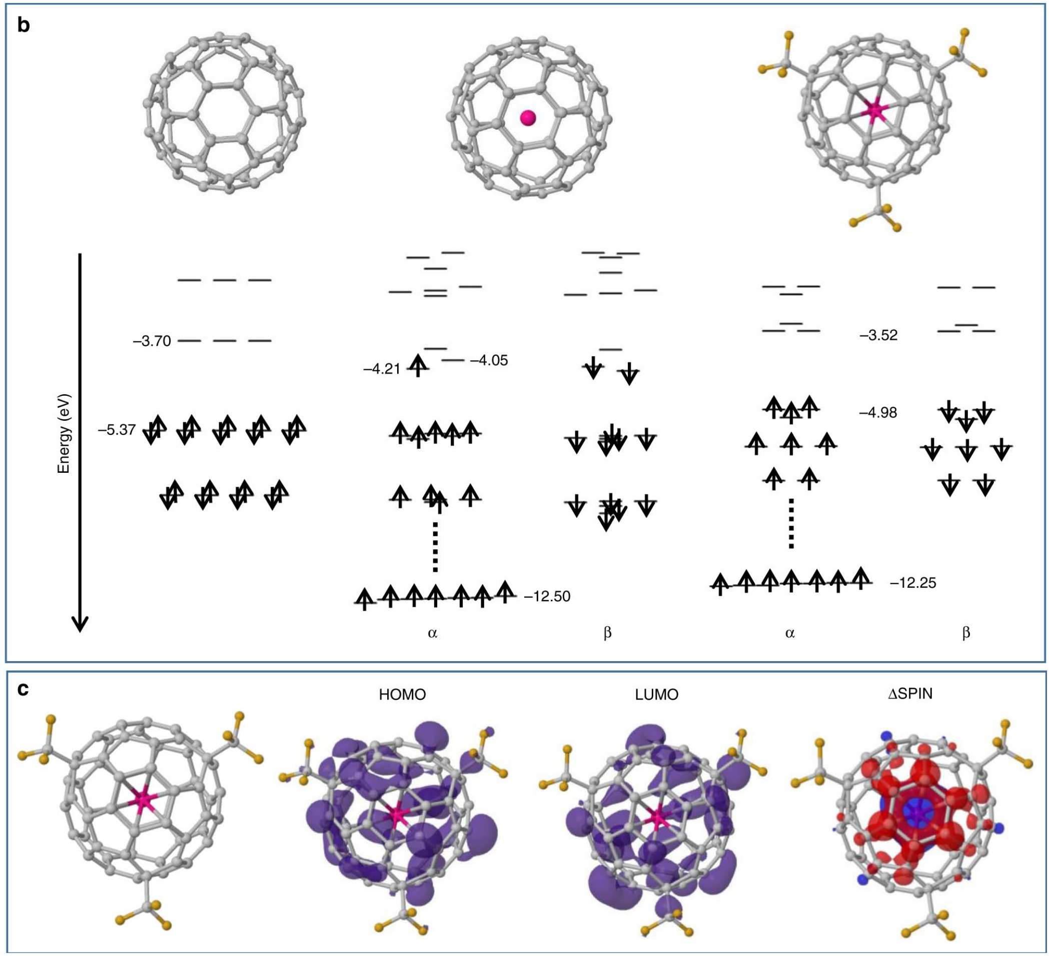
20 hexagons and 12 pentagons

https://www.ch.ic.ac.uk/local/projects/unwin/Fullerenes.html

Fullerene



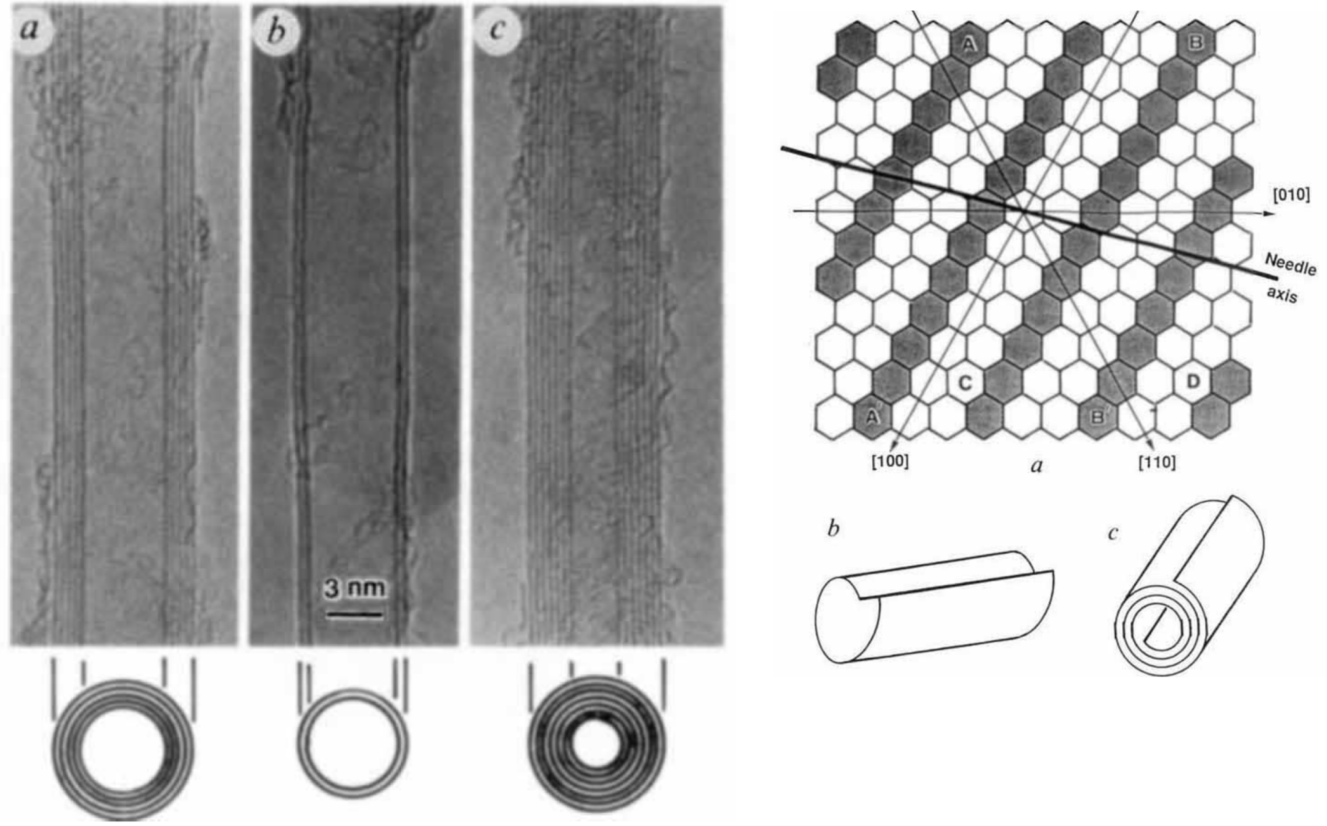
A. Nakagawa et al. Nat. Commun. 2018



- One can use C60 to form various compounds.
- Even control the band structure
- Many applications in chemistry, biology, and solar cells

Carbon nanotubes

- First discovered by Sumio Iijima at 1991.
- Grown by DC arc-discharge evaporation of carbon which is used to produce the C_{60}



Sumio Iijima Nature (1991)

Carbon nanotubes

The 1D nanostructure with very unique electrical and mechanical properties. It is wildly used in many fields.

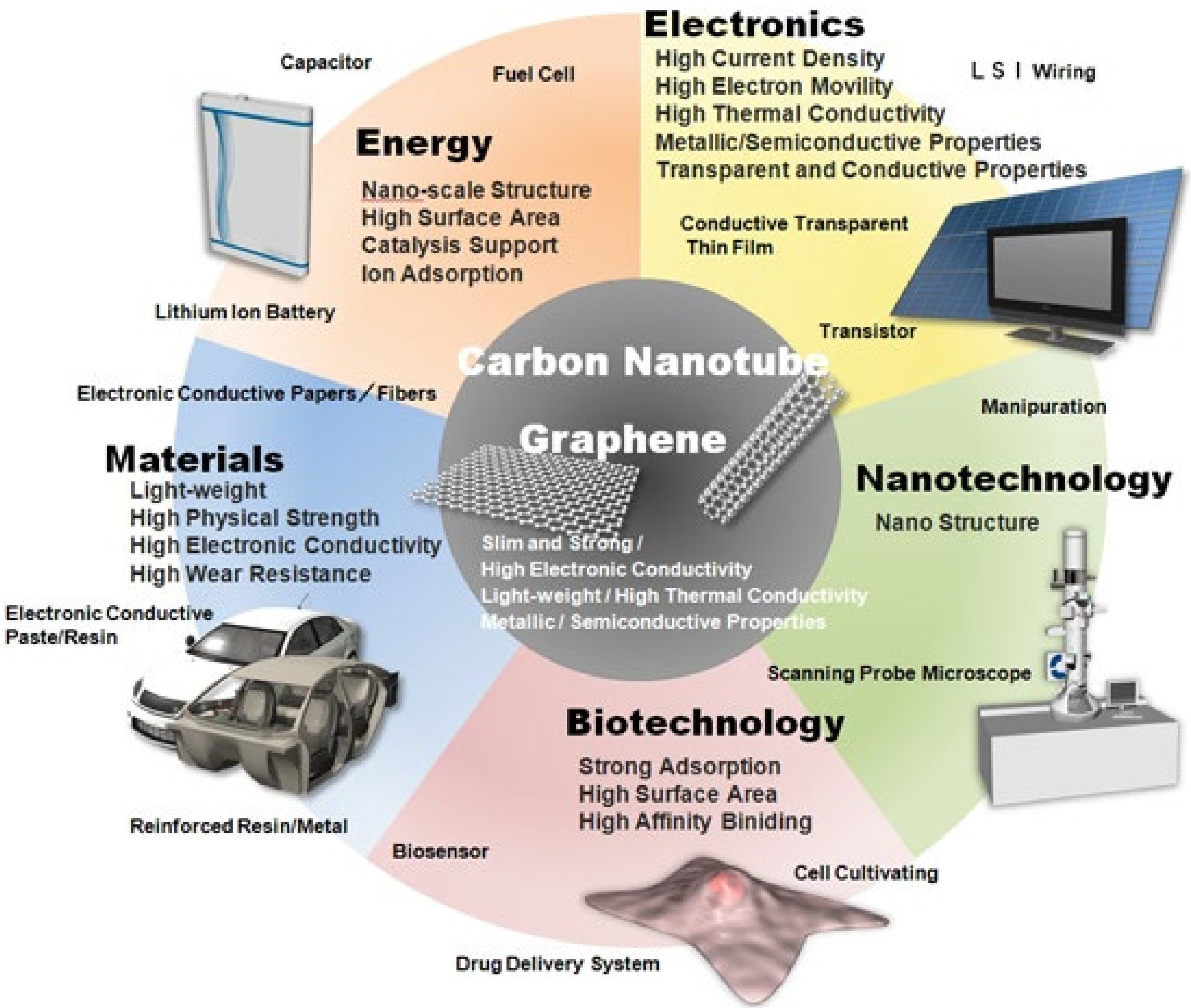
Energy storage and applications

Electronic devices

Material applications

Bio-related applications

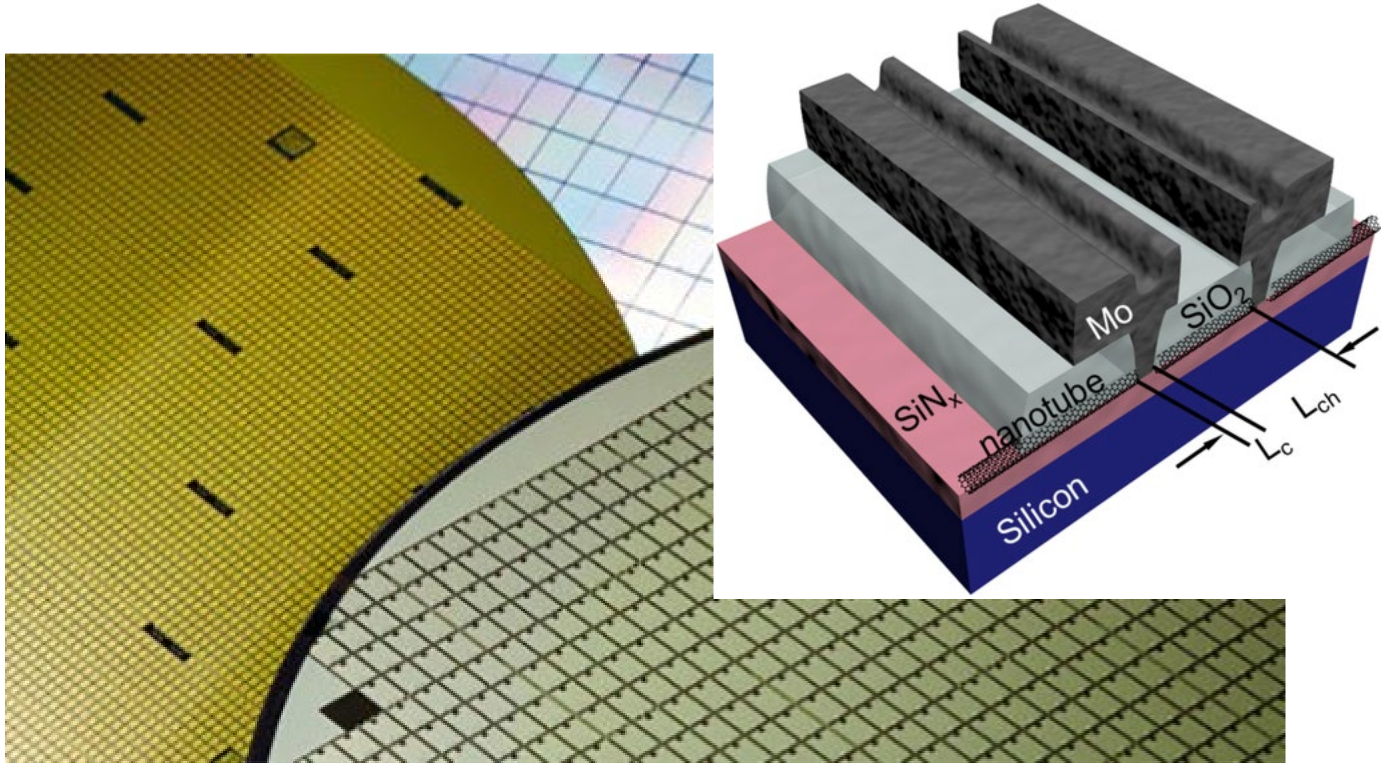
Nanostructure for research



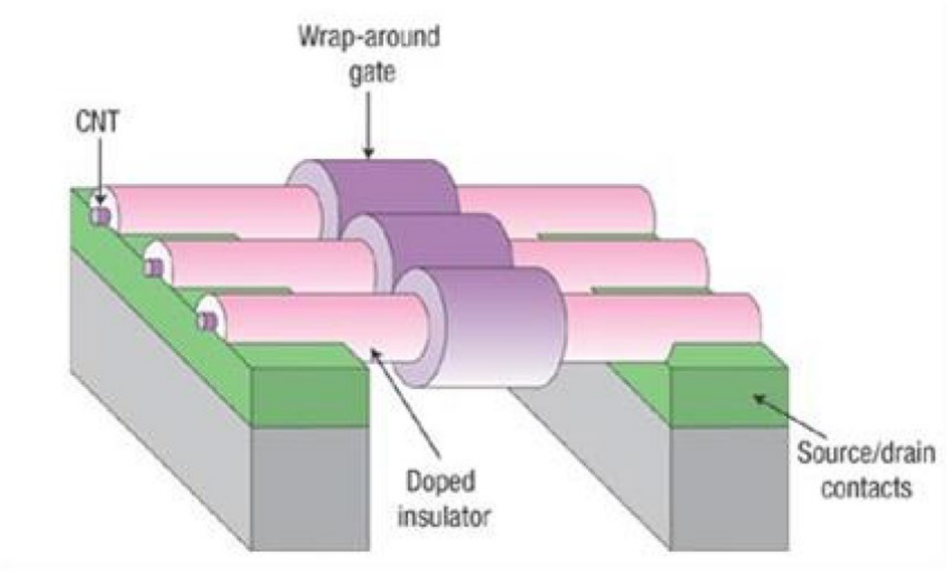
https://meijo-nano.com/en/applications/use.html

Carbon nanotubes

- Use the size of tube to scale down the size of transistors



IBM research



P. Avouris et al. Nat. Nanotech. (2007)

Quote to quote about nanotubes

listening to exciting quotations about CNT:

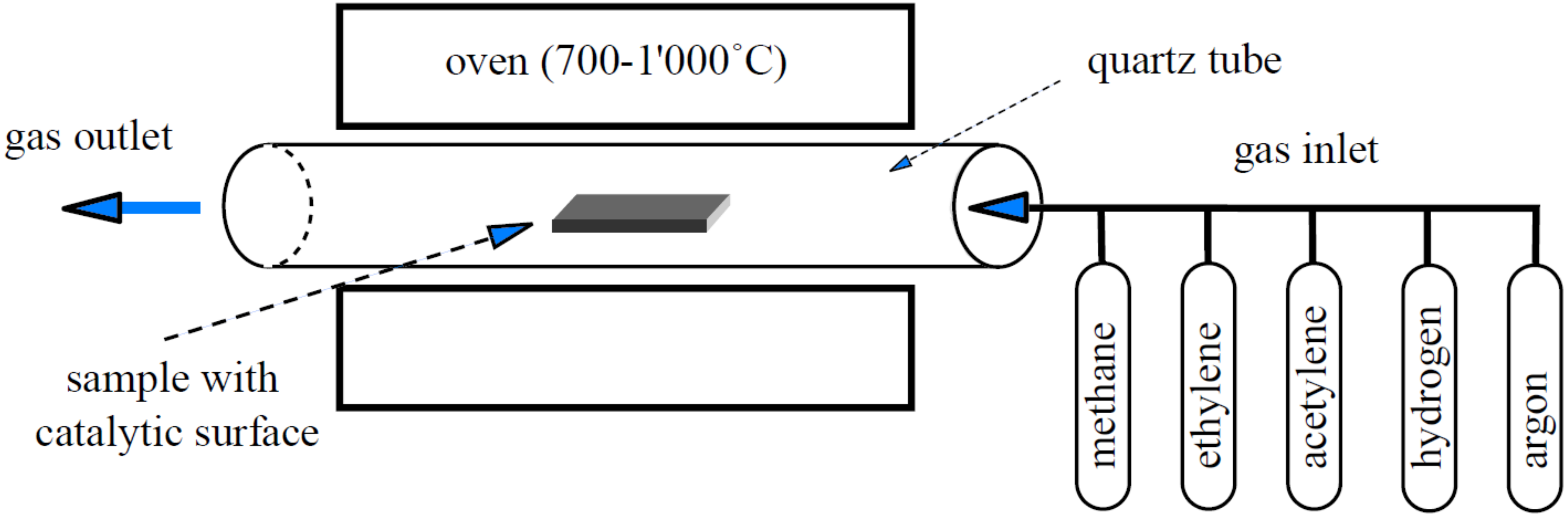
- - "CNT is 100 times stronger than stainless steel and six times lighter…"
- - "CNT is as hard as diamond and its thermal capacity is twice that of pure diamond…"
- - "CNT's current-carrying capacity is 1000 times higher than that of copper…"
- - "CNT is thermally stable up to 4000K…"
- - "CNT can be metallic or semiconducting, depending on their diameter and chirality…"

That all make CNT a very compelling system to work on.....

Mukul Kumar
ISBN: 978-953-307-497-9

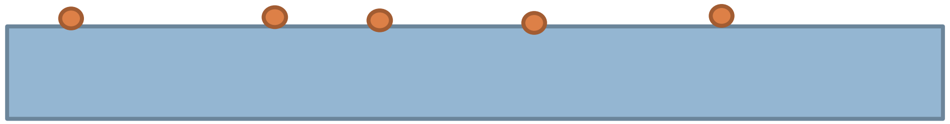
Growth of SWNTs

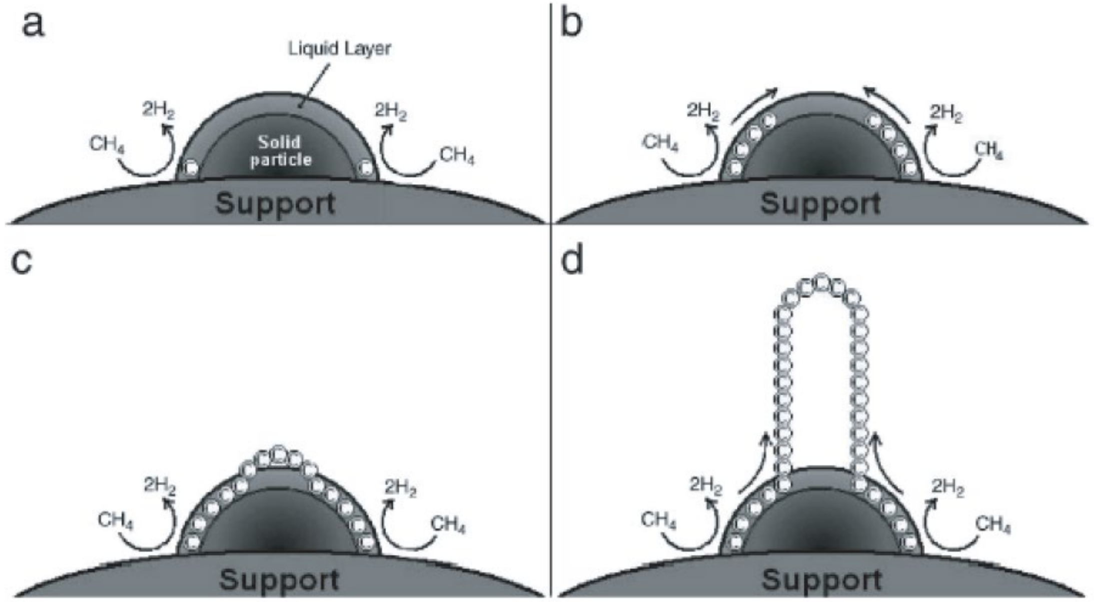
Typical method: chemical vapor deposition



Growth of SWNTs

- The carbon needs to attach to something like dirt or debris.
- This usually can be done purposely, it is called catalysts.
- The typical catalyst: Fe, W, Ni Au, etc. based nanoparticles.
- Very high growth rate 60 μ m/min

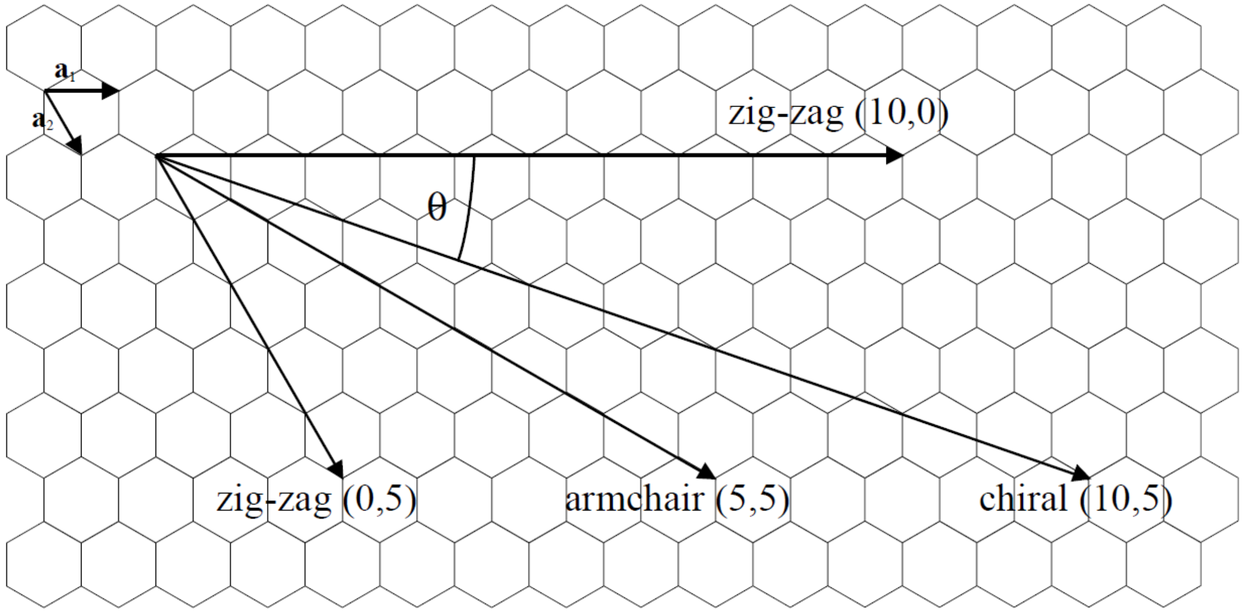




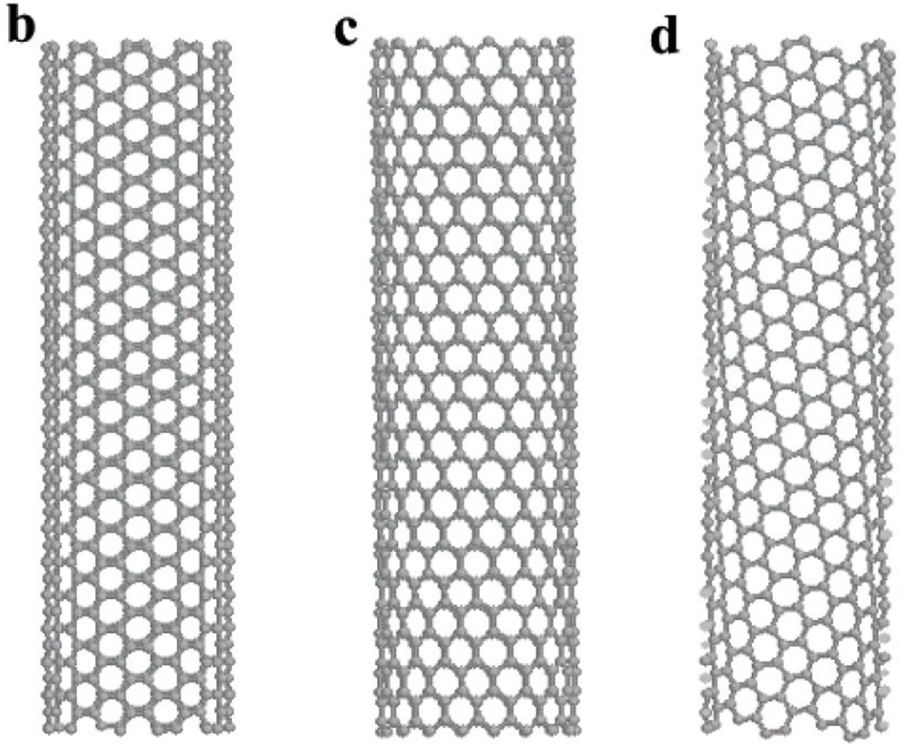
Type of CNTs

One can fold a graphene sheet in different directions:

The folded direction can be decided by the coordinate (n,m)

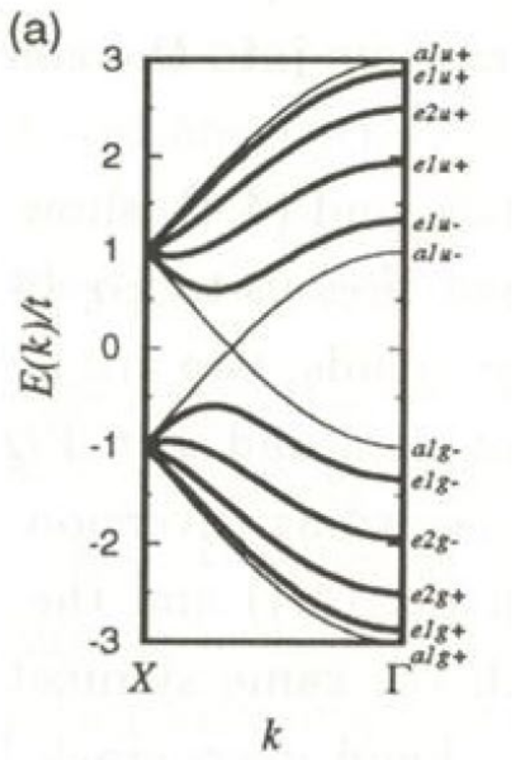


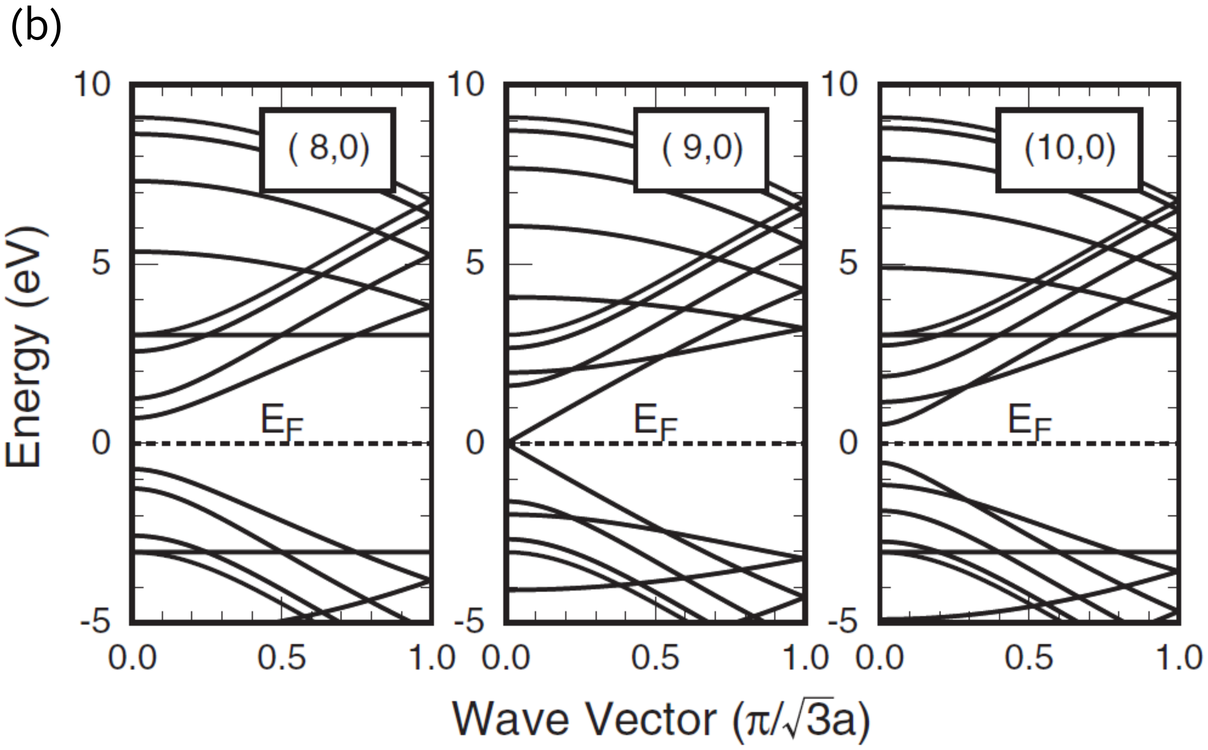
HongJie, Dai, Acc. Chem. Res. 35 (2002)
JÄurg Furer thesis, (2006)



Armchair(n,n) Zigzag (n,0) Chiral (10,5)

Band structure





For SWNT,
The (n,m) can determine the diameter d and chiral angle θ.

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

$$sin\theta = \frac{\sqrt{3}ma}{2d\pi}$$

General rule: n-m=3l, metallic n-m=3l±1, semiconductor.

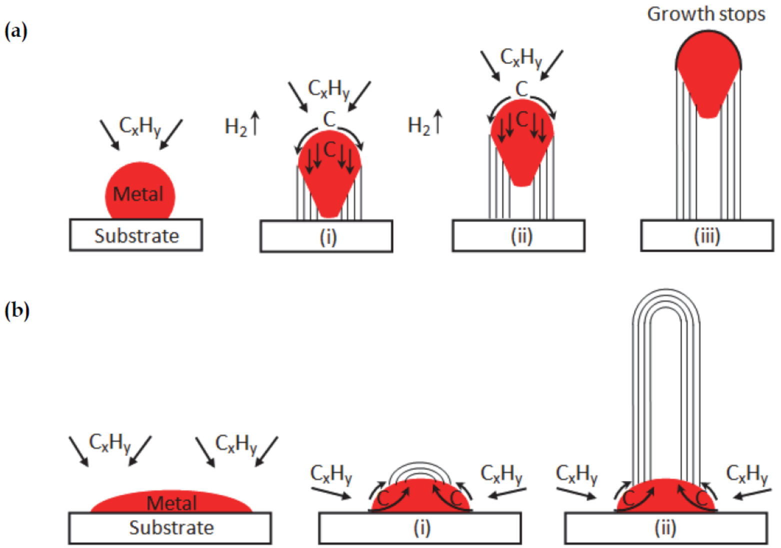
(a) Armchair (metallic)   (b) Zigzag(semiconductor or semimetal)

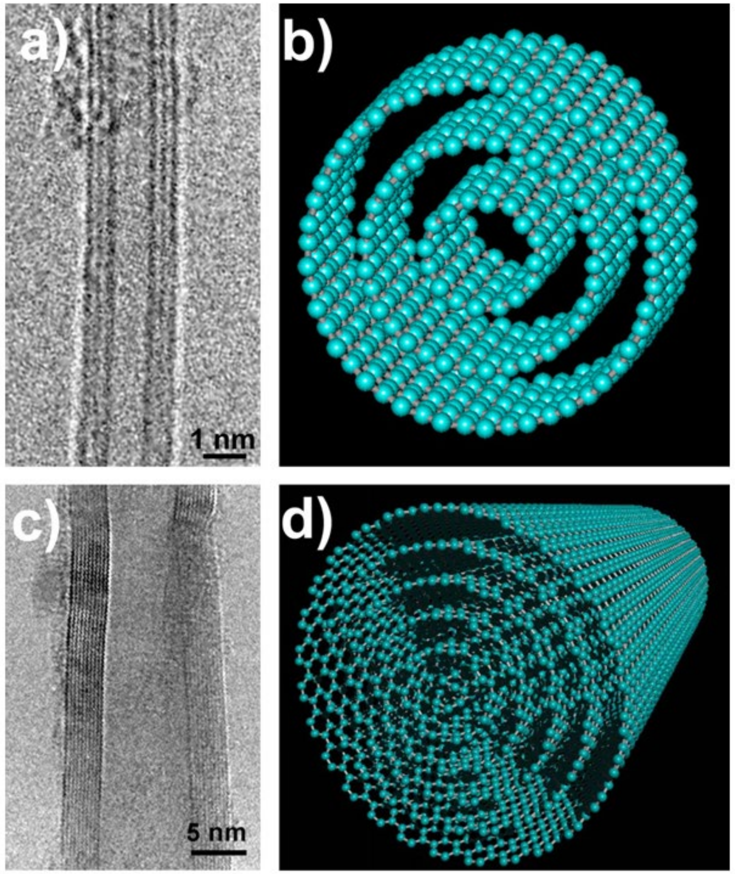
Two types of tubes are semiconductor and metallic.

R. Saito et al. Physical properties of carbon nanotubes. (1998)
Tsuneya ANDO 0.1143/JPSJ.74.777 (2005)

Multi-wall nanotubes

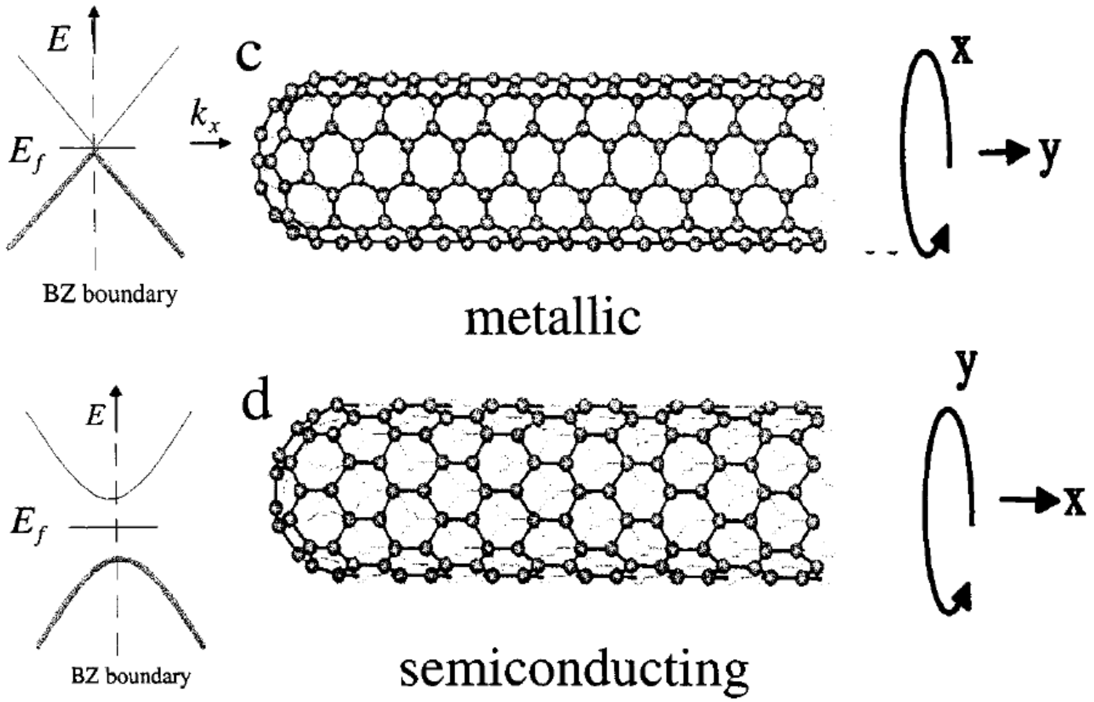
- Usually grown at a lower temperature, 750 C
- Still possessing very good properties, high tensile strength, good hardness, conductivity, thermal properties etc.



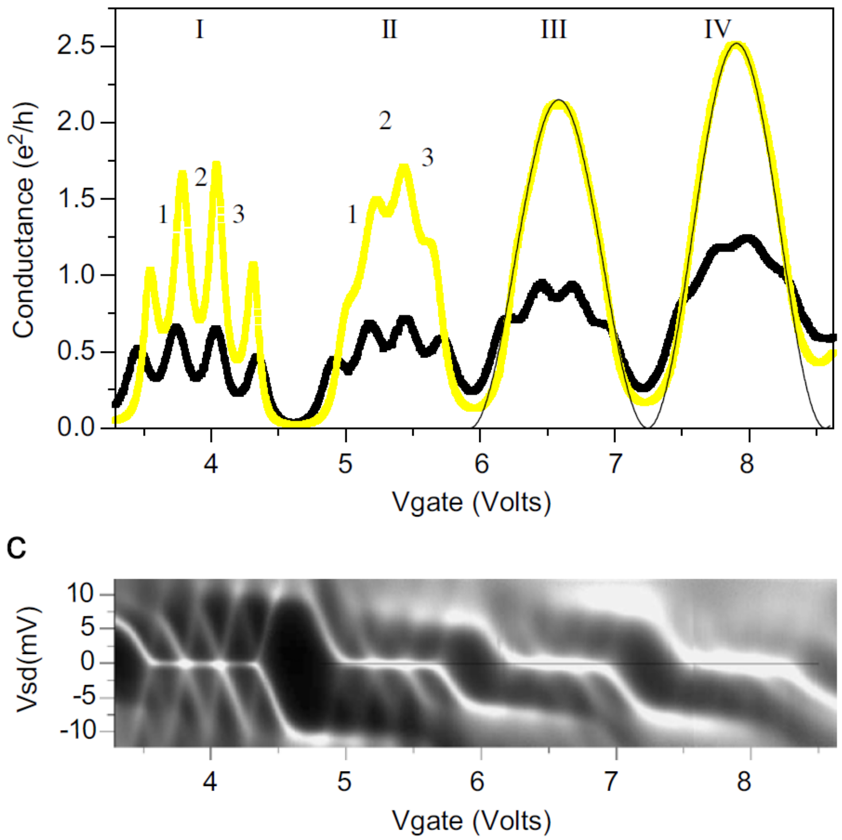


Mukul Kumar ISBN: 978-953-307-497-9

Symmetry of the tubes



Paul L. McEuen, et al. IEEE trans. on nano. (2002)

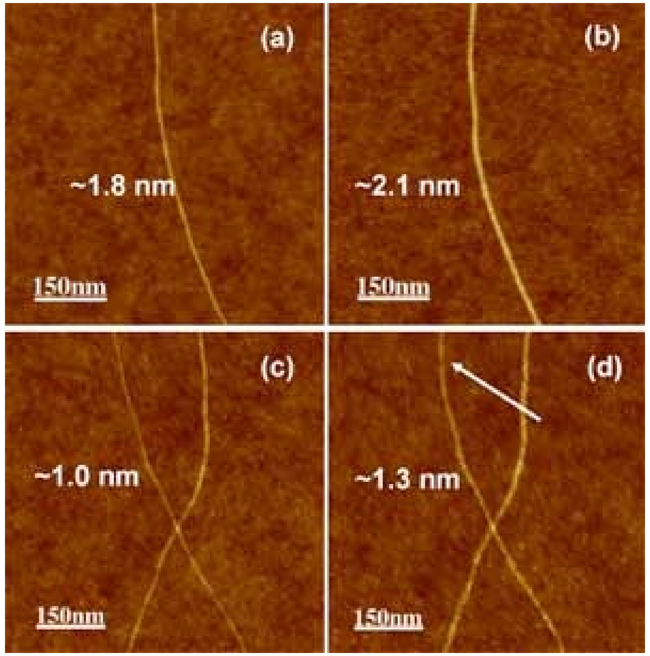


A. Makarovski, G. Finkelstein, Physica B(2008)

- Chiral + Spin leads to a four-fold degeneracy of SNT

Tube characterization

- AFM/SEM/TEM



Credit: Anton Nikitin, SSRL

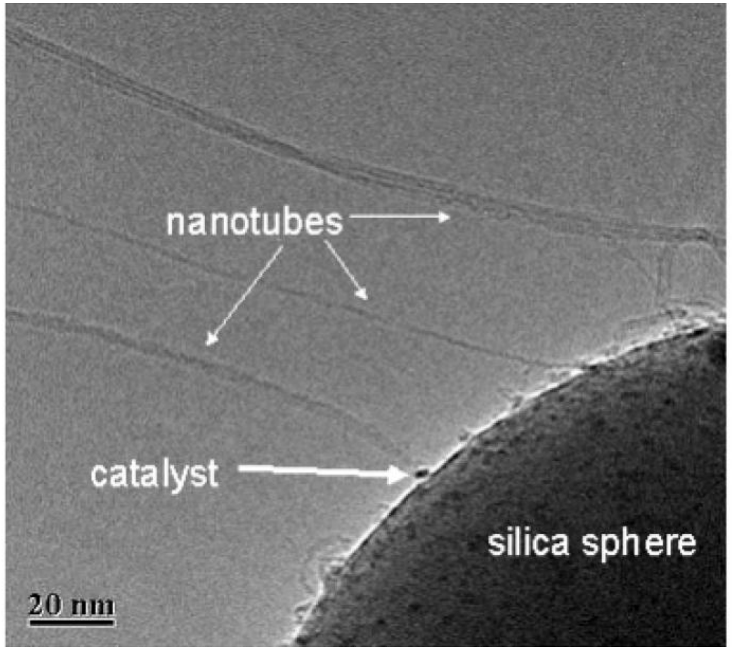
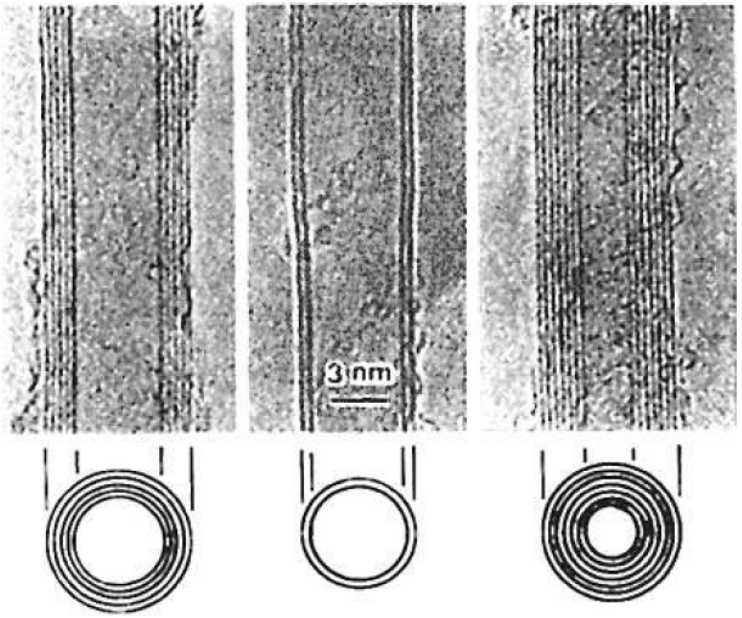


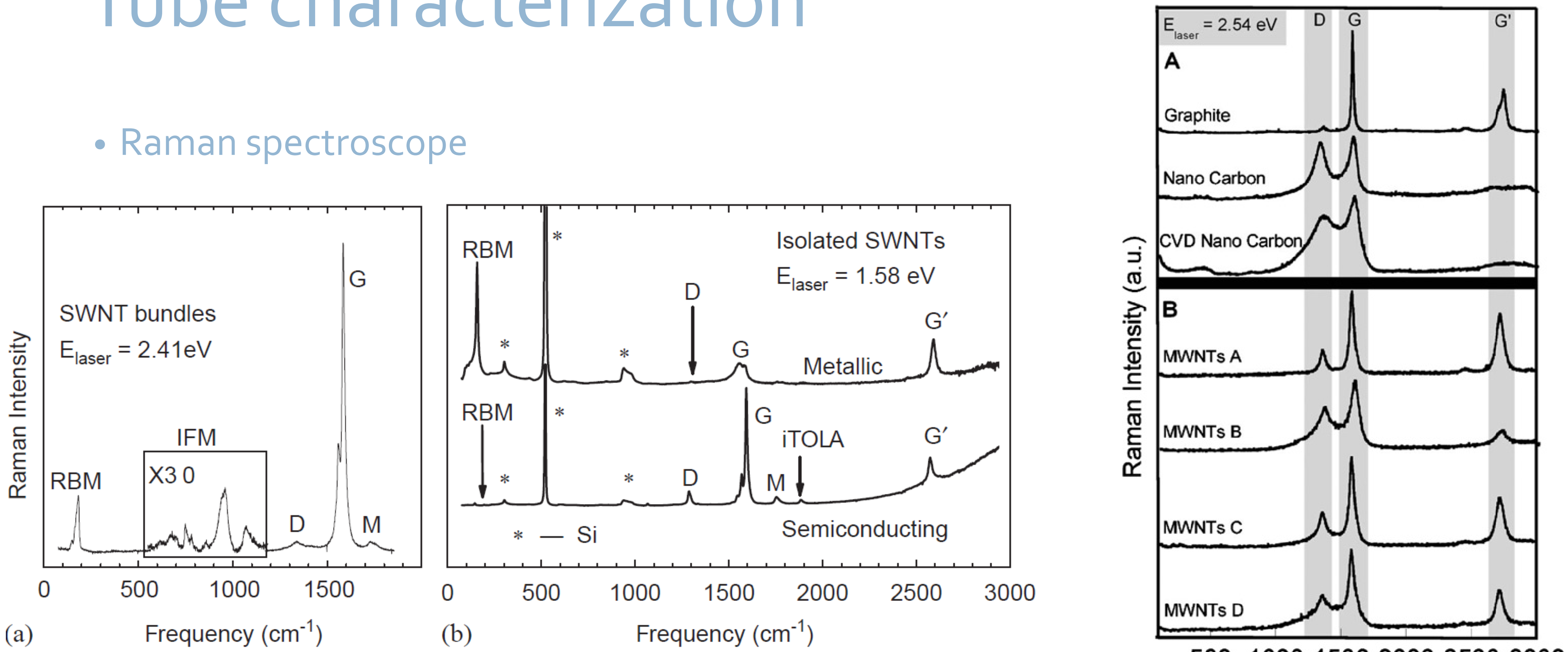
Image: NJIT SEM



JÄurg Furer thesis, (2006)

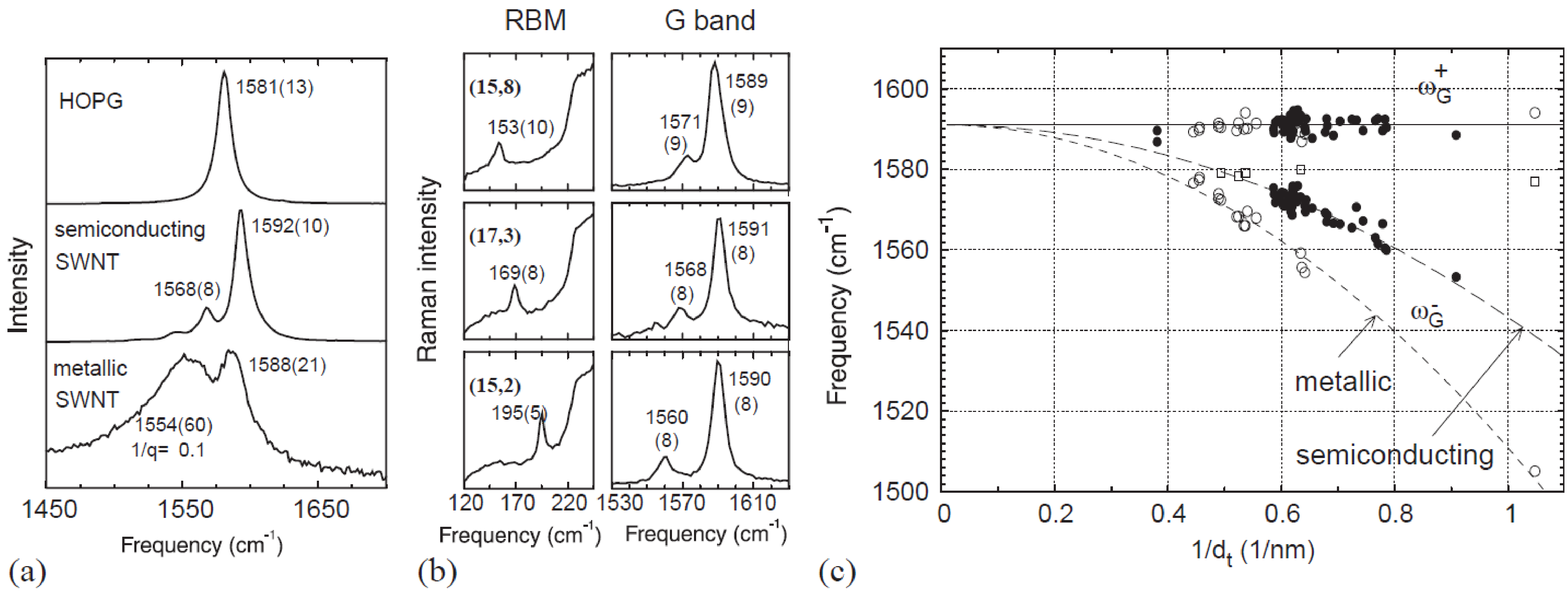
Tube characterization

- Raman spectroscope



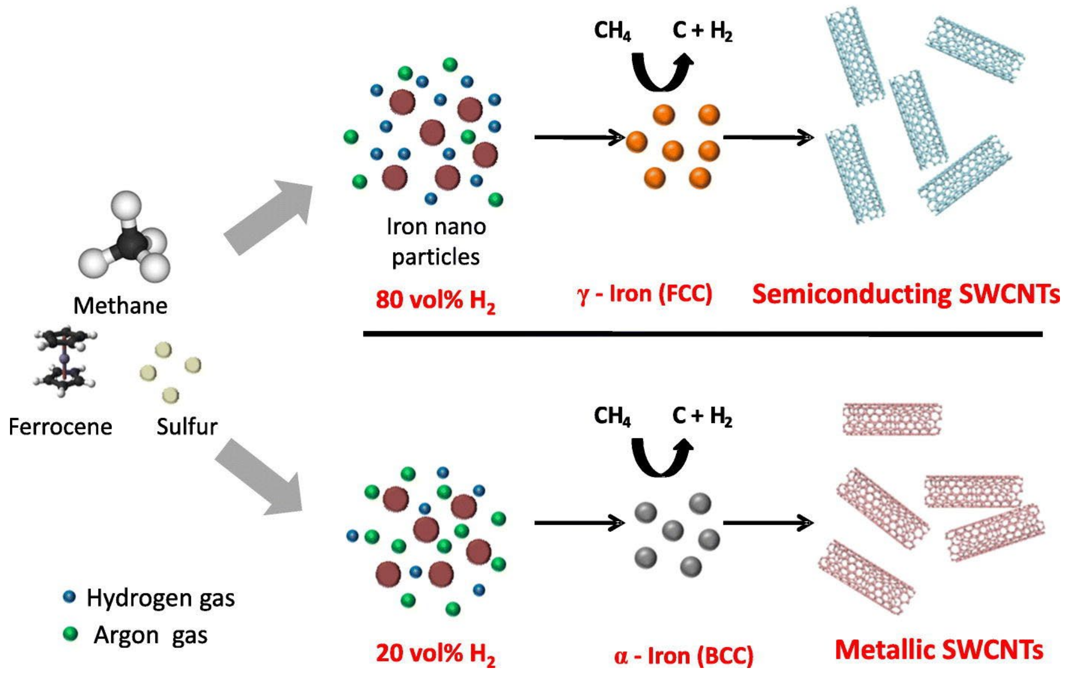
M. S. Dresselhaus et al. Physics Reports (2005)

Selective growth or filtering

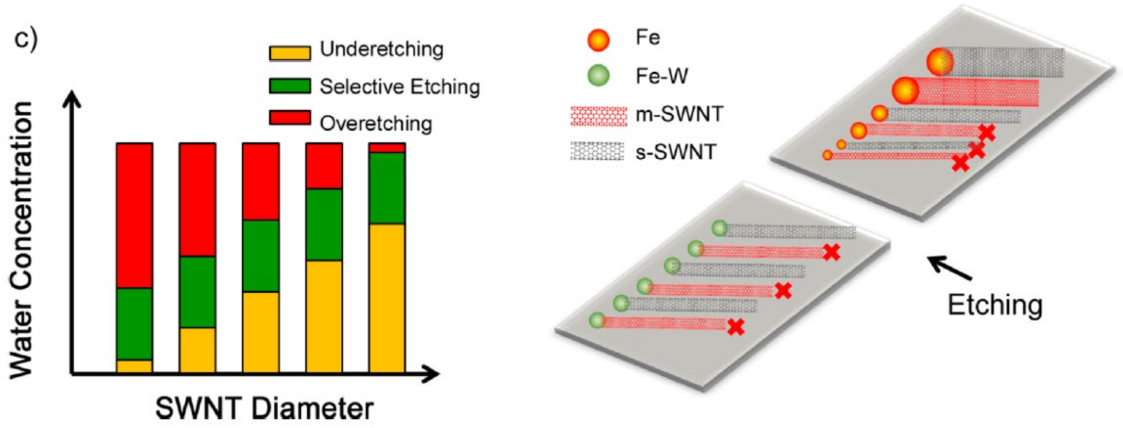


- Selected by Raman spectra

Selective growth or filtering



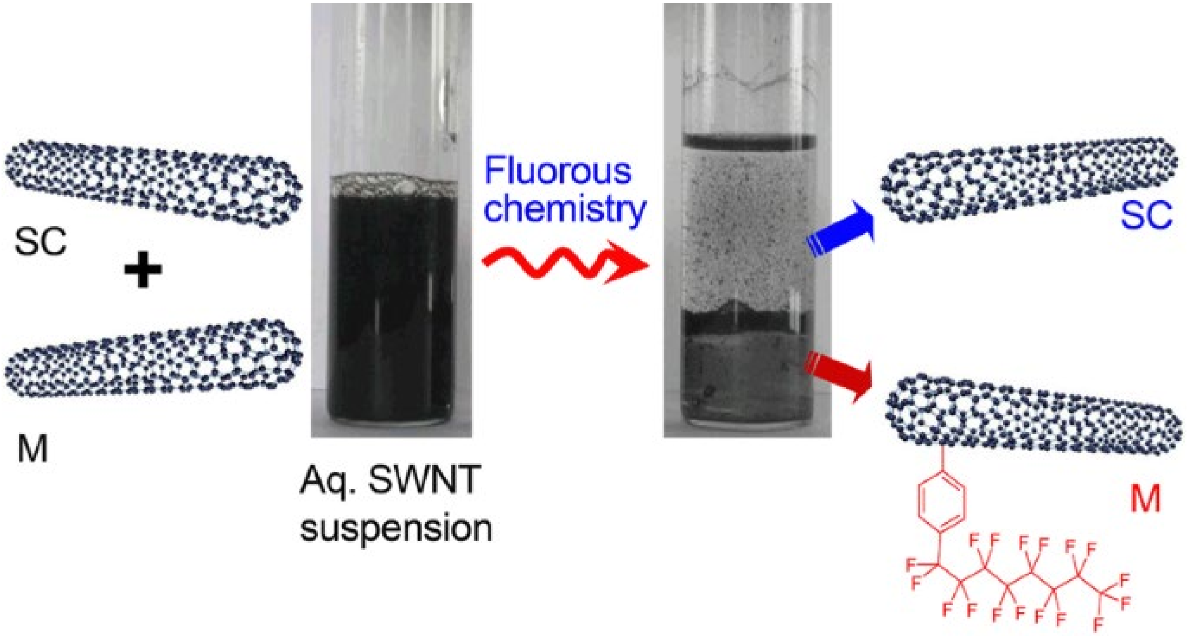
M. D. Yadav, et al. (2019)



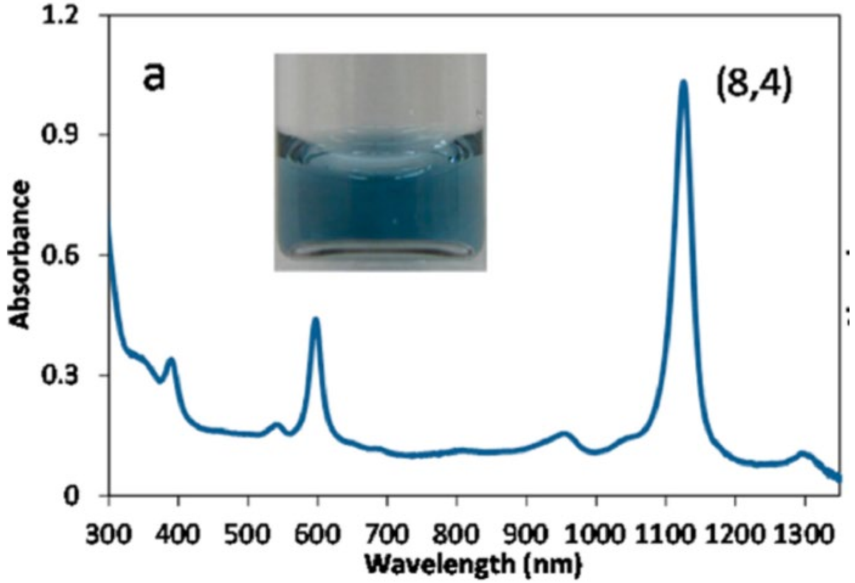
J. Li, et al. ACS nano (2014)

- Control of catalyst is the key to selectively growth CNTs

Selective growth or filtering



S. Ghosh & C. N. R. Rao, Nano Research (2009)

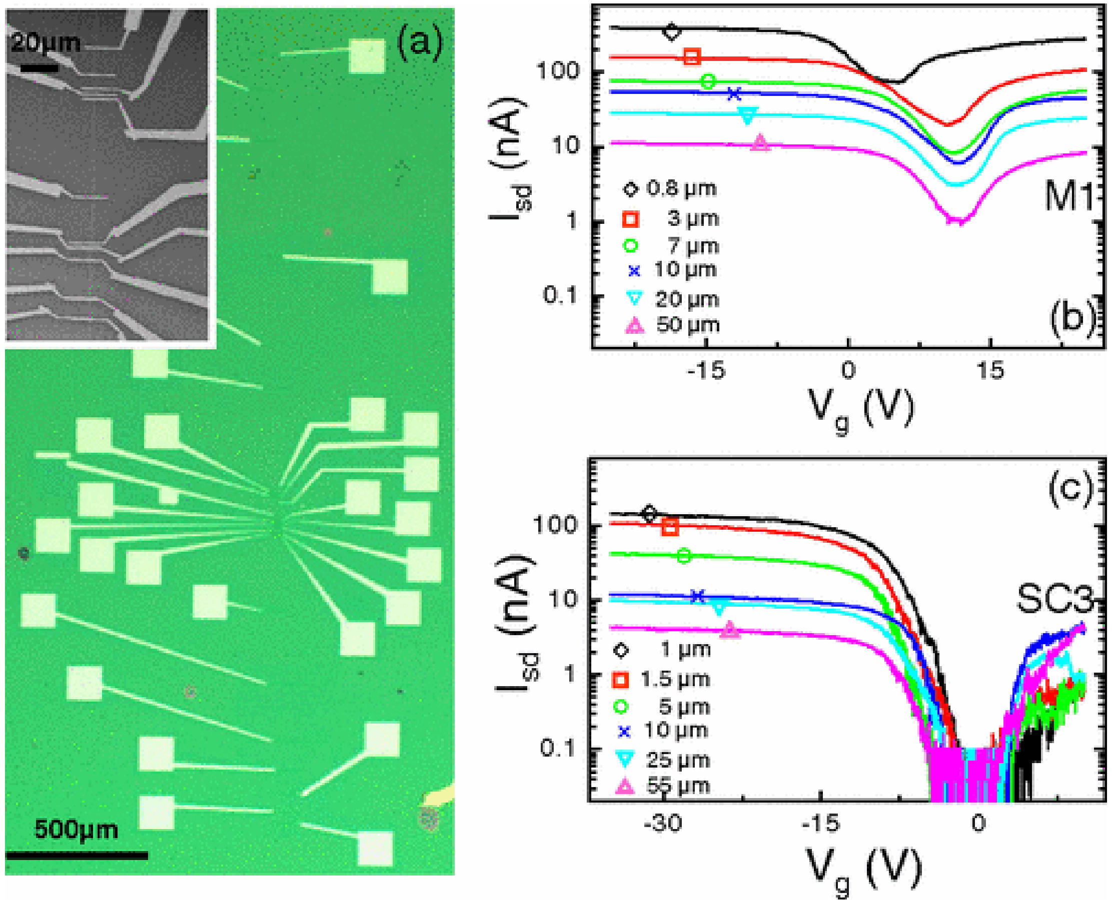


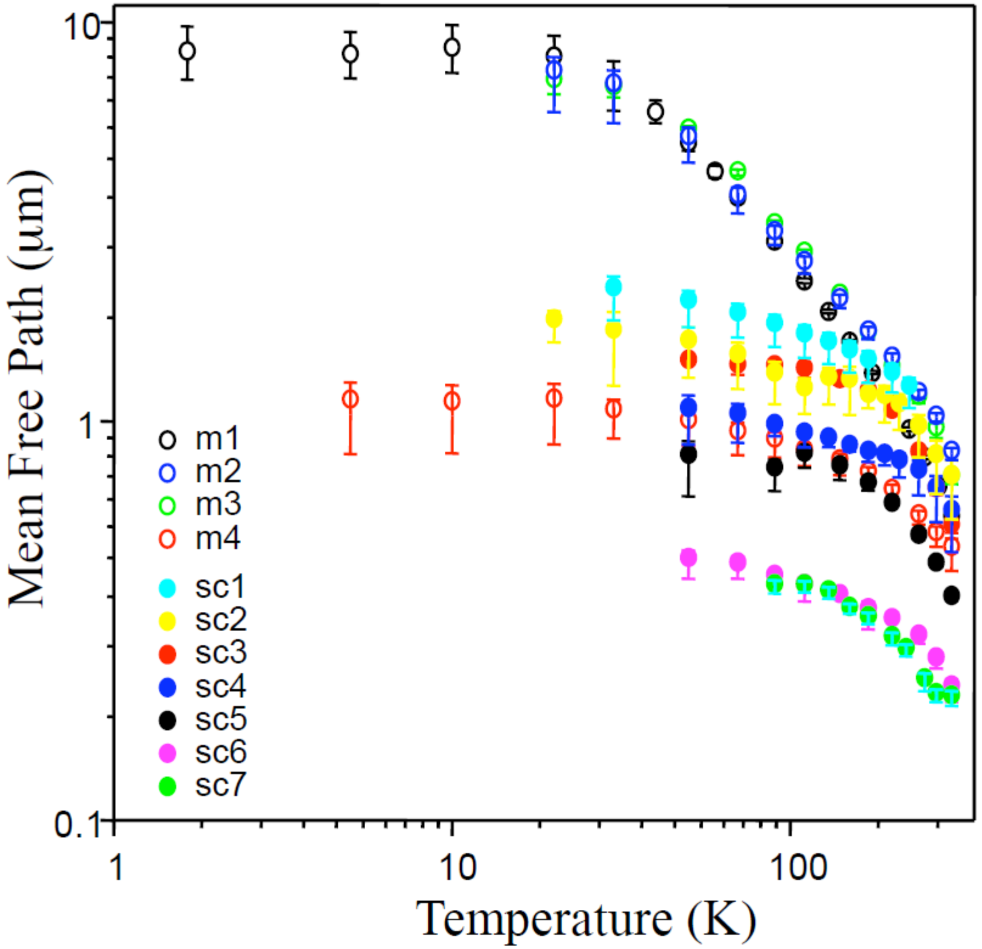
M. S Y Tang, et al. Nanotechnology (2016)

- Purification with chemistry methods

High quality 1D wire

$$R(L) = \left(\frac{h}{4e^2}\right)\left(\frac{L}{L_m} + 1\right) + R_c$$

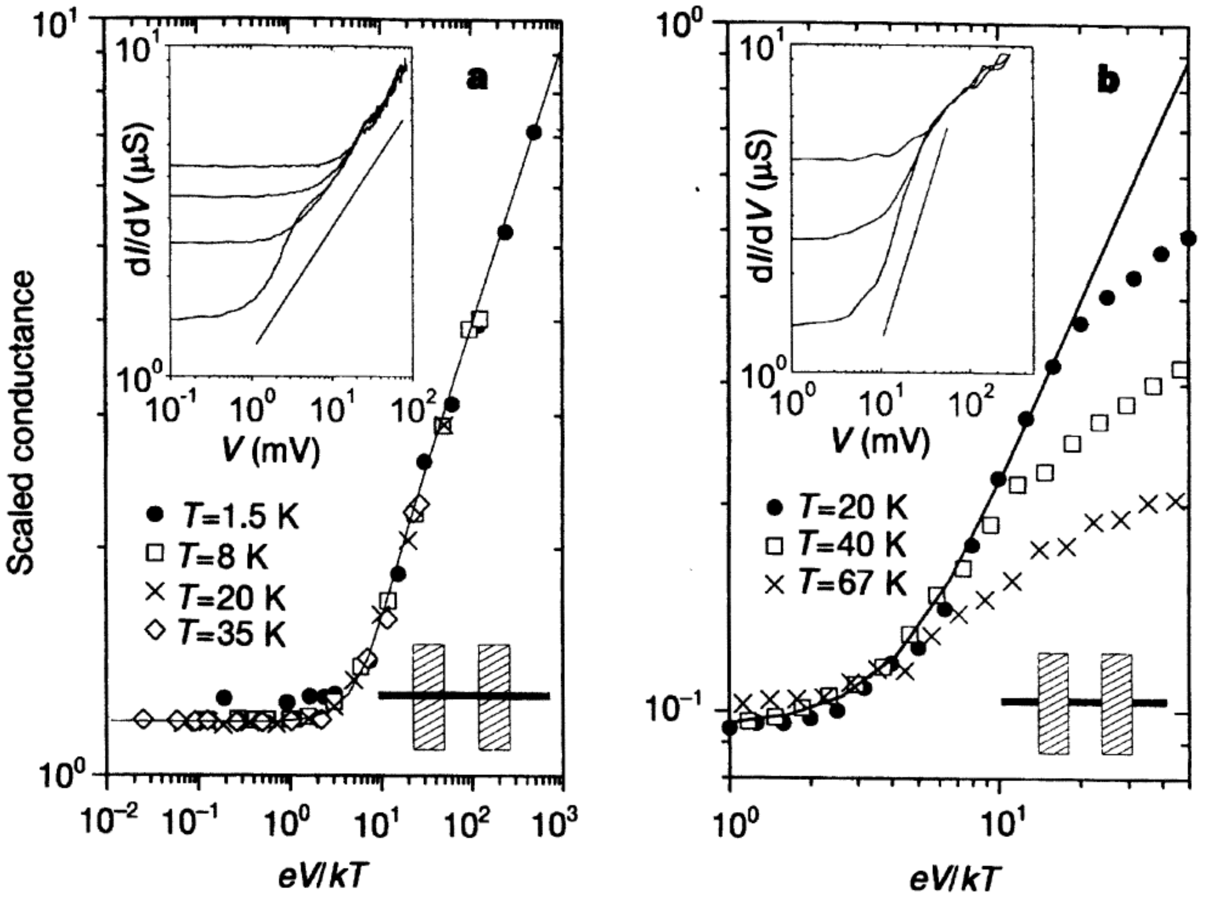




Temperature dependence:

Luttinger liquid

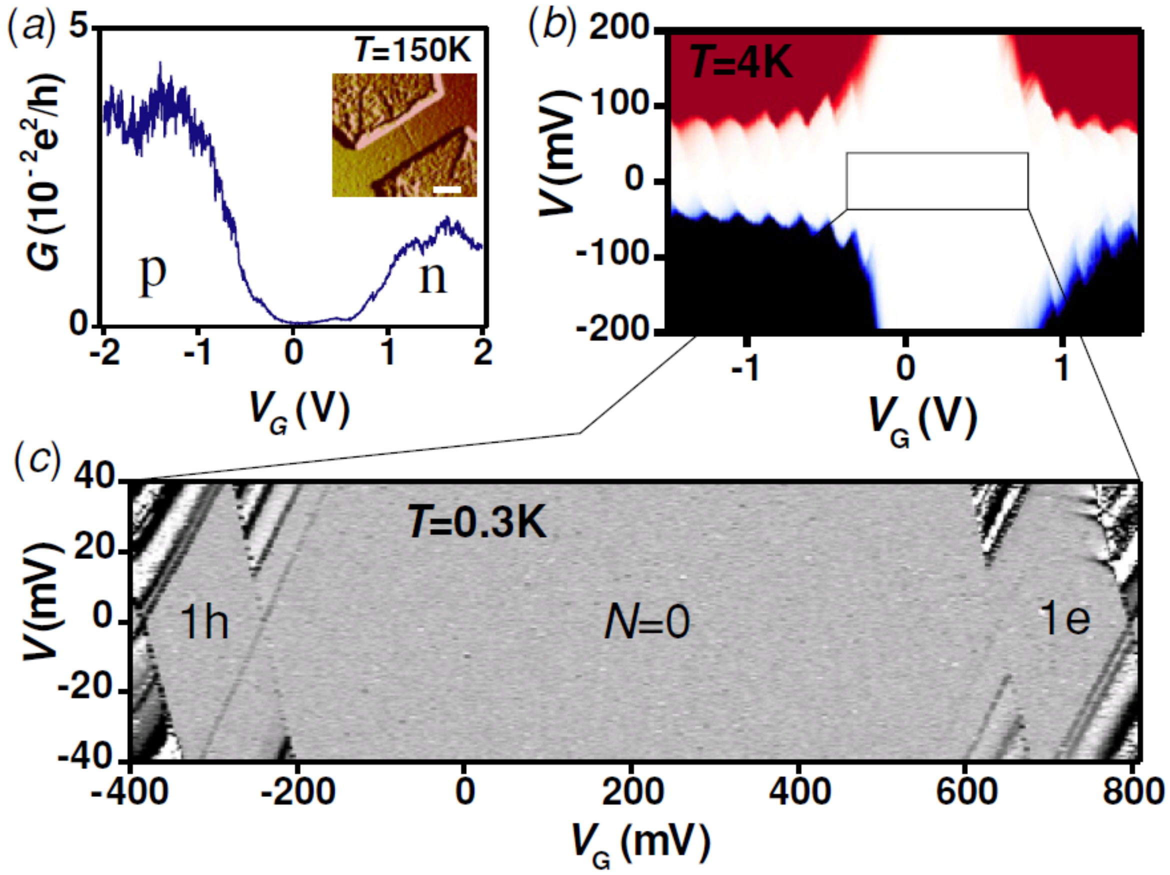
- An interaction picture for a 1D conductive system when Fermi liquid breakdown.
- The low energy excitation electron can be described by Boson instead of Fermion.
- Power law dependence in temperature was observed in the 1D carbon nanotubes.



M. Bockrath, et al. Nature (1999)

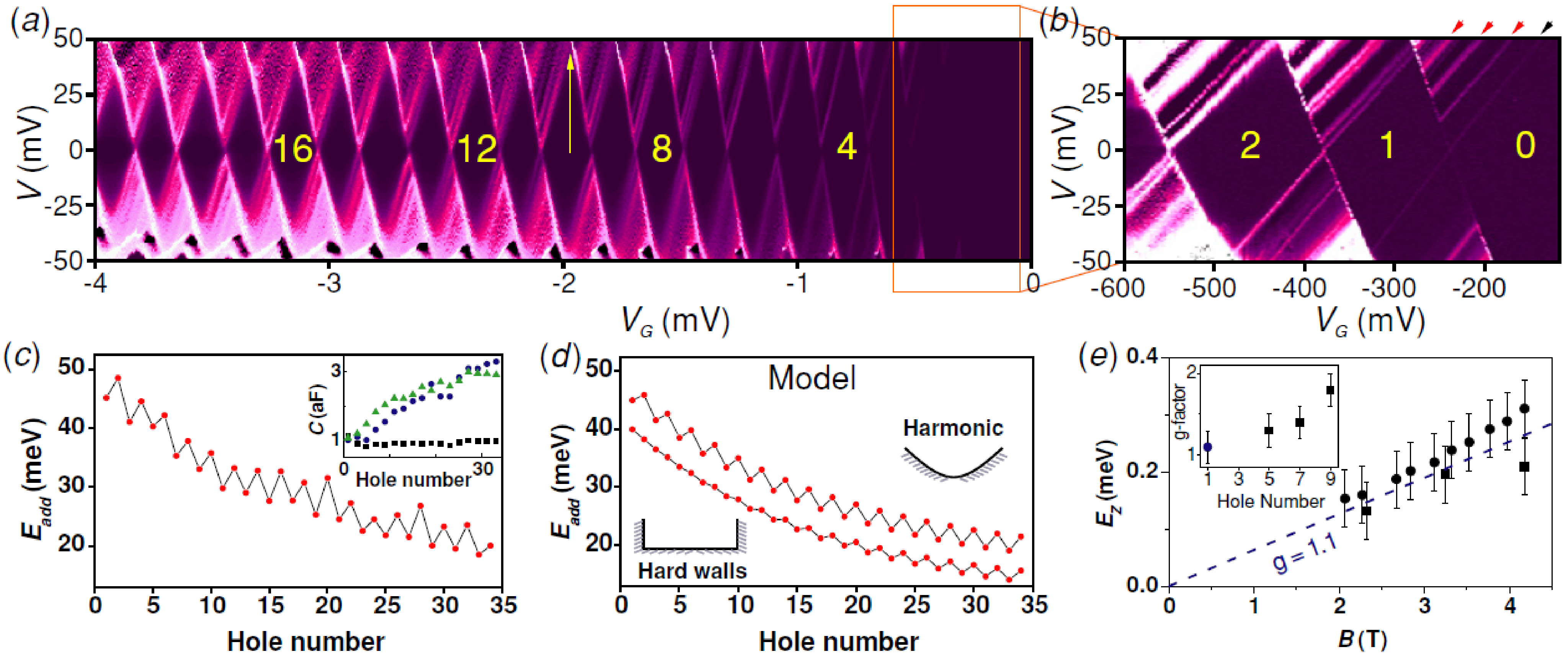
CNT quantum dot

- The clean 1d quantum wires make an easy route to create the zero-dimensional quantum dots.
- The quantum dot can be defined by adding metal contact to CNT with a designed distance.
- At a low enough temperature, quantization can be revealed. Therefore, one can count electrons one by one which knows as a single-electron transistor.



Sami Sapmaz et al. Semicond. Sci. Technol. 21 (2006)

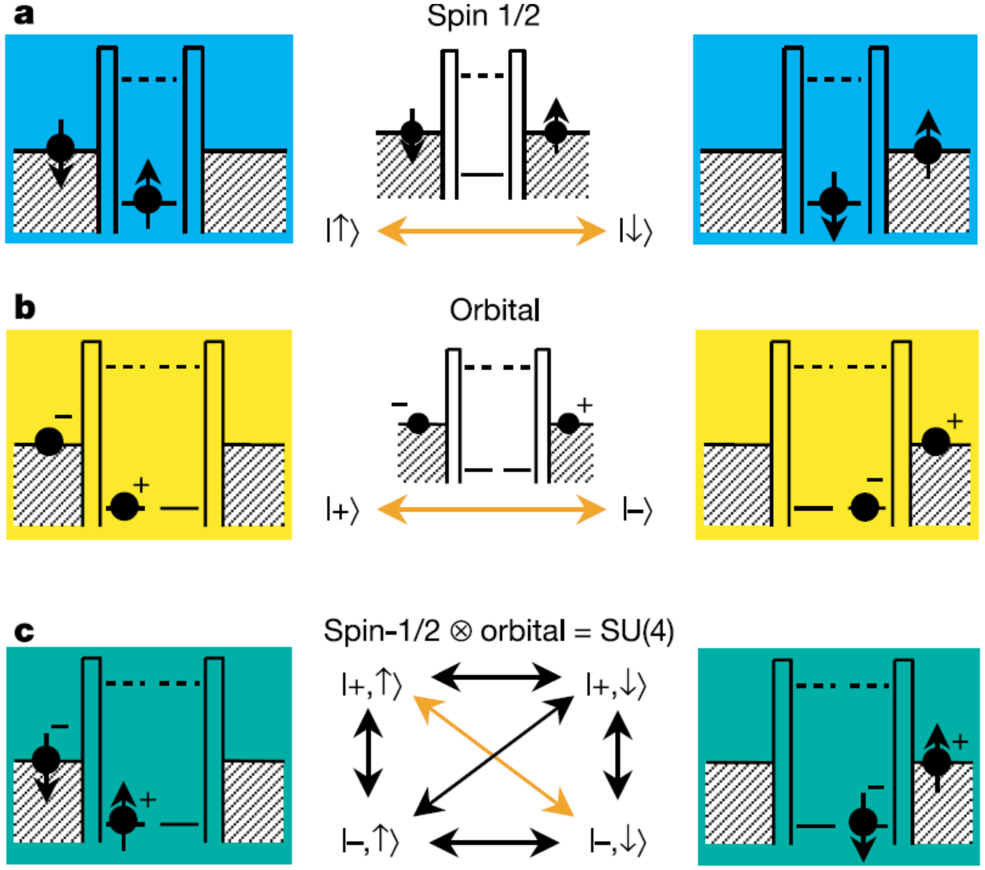
CNT quantum dot



Sami Sapmaz et al. Semicond. Sci. Technol. 21 (2006)

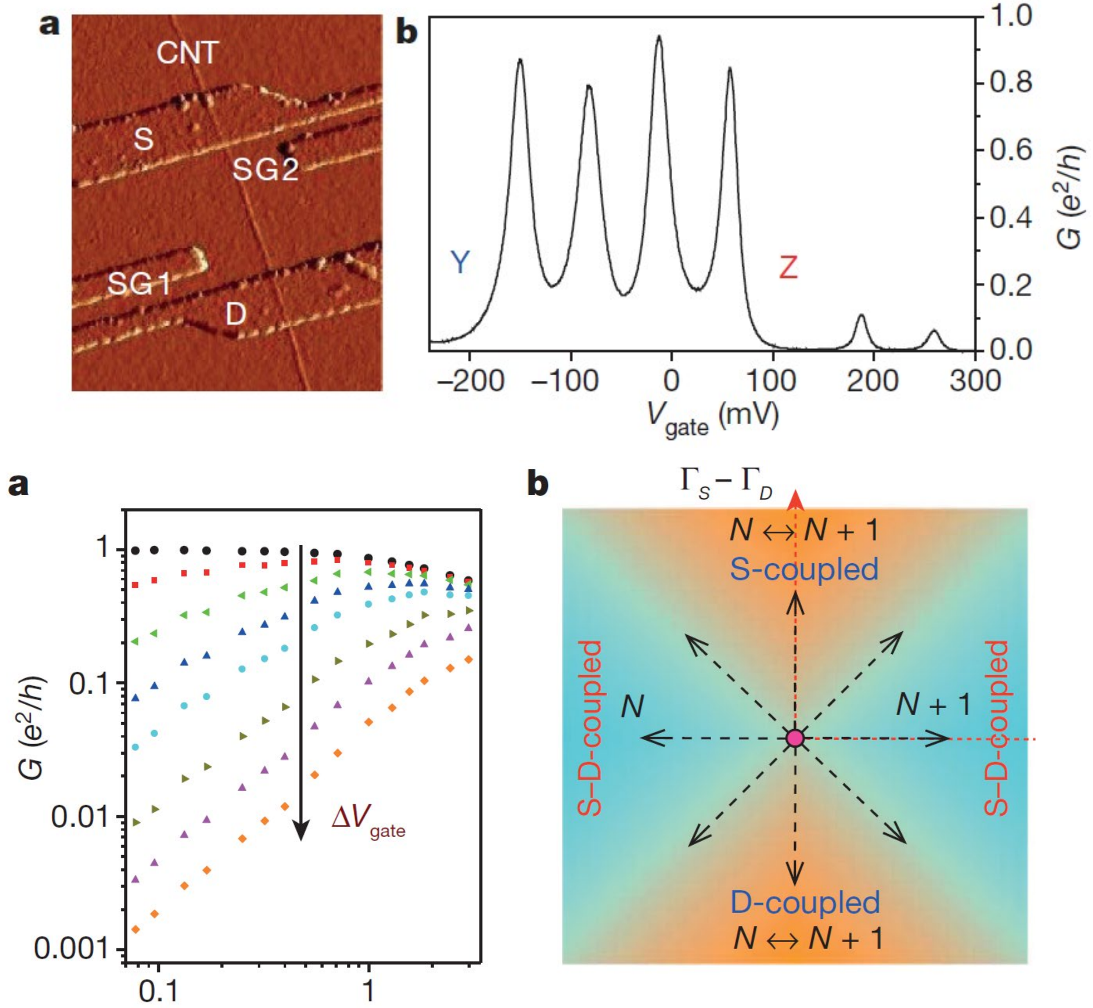
CNT quantum dot

Kondo effect



P. Jarillo-Herrero et al. Nature (2005)

Quantum phase transition



H. T. Mebrahtu et al. Nature (2012)

Quiz

- 1.which one is the 1D carbon materials

  A graphene　　　　　　　　　　B carbon nanotube

- 2. what is the difference between ebeam lithography and photo lithography(EUV)