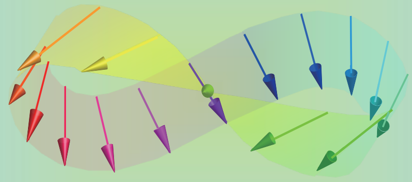
Nanoelectronics
17



Atsufumi Hirohata

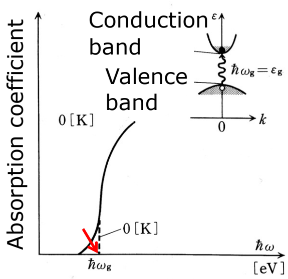
Department of Electronic Engineering

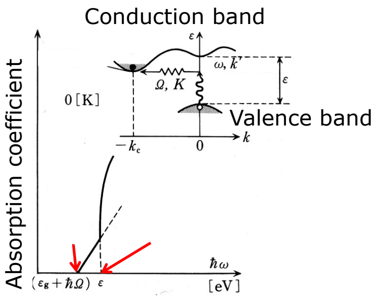
THE UNIVERSITY *of York*

09:00 Thursday, 16/March/2023 (P/T 005A)

Quick Review over the Last Lecture

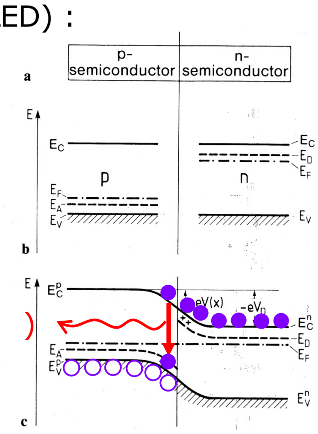
Optical absorption :



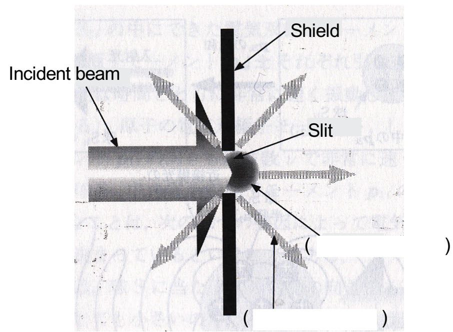


Light emitting diode (LED) :

( )



Near-field optics :



Contents of Nanoelectonics

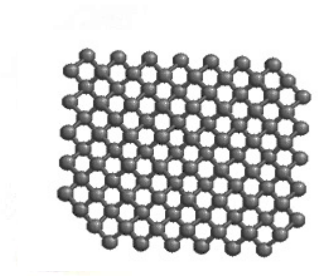
17 Organic Nanodevices

- Carbon nanotube
- Graphene
- 1D electron transport

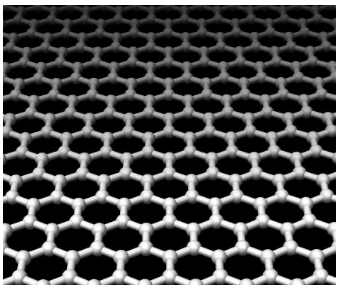
Organic Materials

Organic materials include a carbon atom :

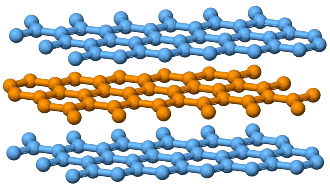
Diamond :

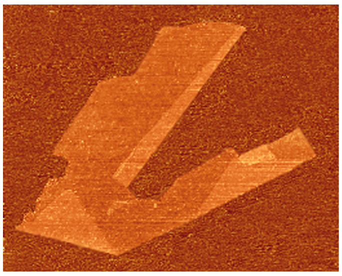


Graphene was predicted by Philip R. Wallace in 1947 :



In 2004, Andre K. Geim and Konstantin S. Novoselov successfully isolated a single-layer graphene :



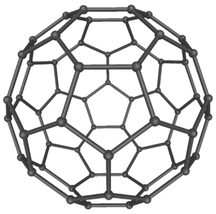


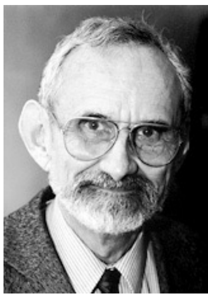
"Scotch tape method"

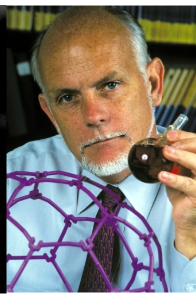
* http://www.wikipedia.org/
** K. S. Novoselov *et al.*, *Science* **306**, 666 (2004).

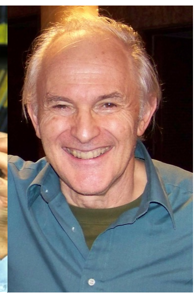
Discovery of a Fullerene

Fullerene was discovered in 1985 by Robert F. Curl, Jr. and Richard E. Smalley at Rice University, and Sir Harold W. Kroto at the University of Sussex :







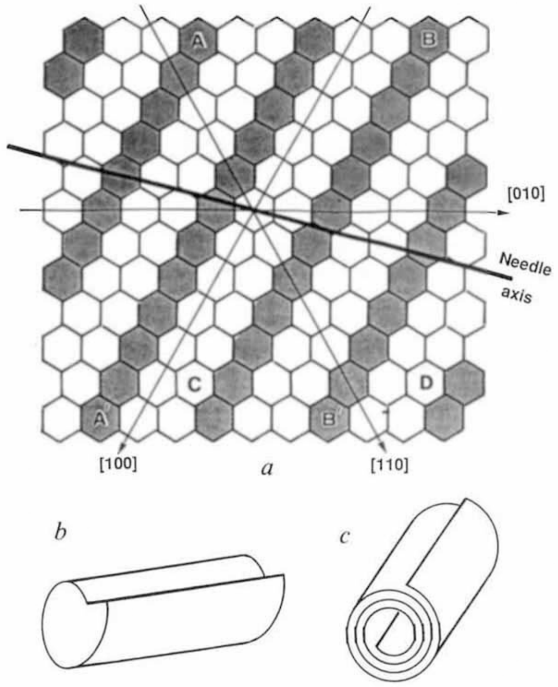


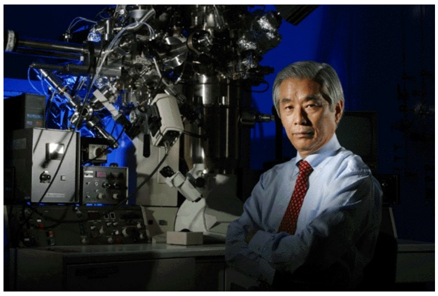
named after Richard Buckminster Fuller.

* http://www.wikipedia.org/
** http://nobelprize.org/

Discovery of a Carbon Nanotube

By rolling a sheet of graphene, Sumio Iijima formed a carbon nanotube (CNT) in 1991.



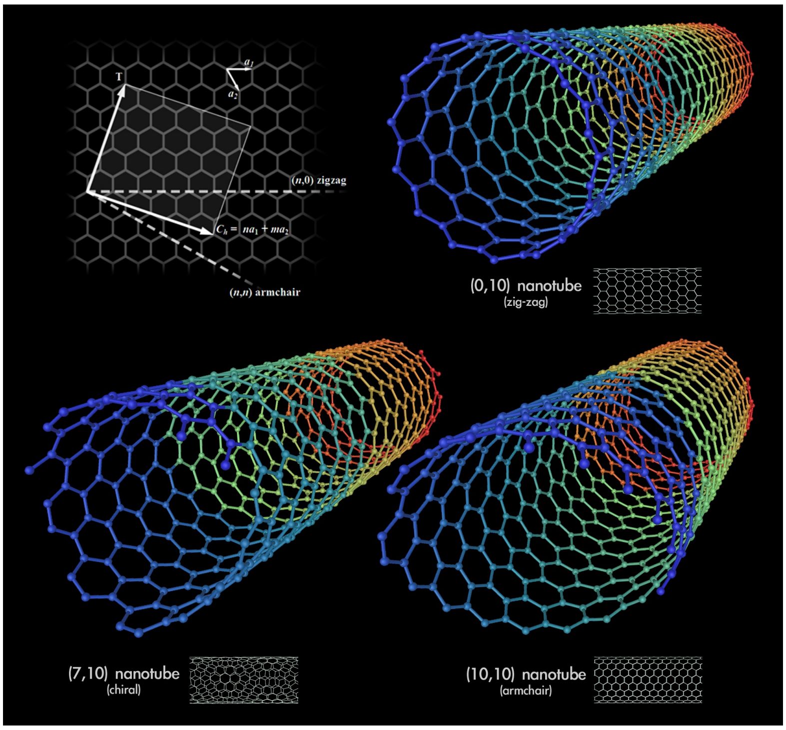


* http://nanocarb.meijo-u.ac.jp/jst/iijima.html

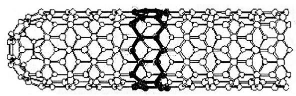
** S. Iijima, *Nature* **354**, 56 (1991).

CNT Types

Three types of CNTs :

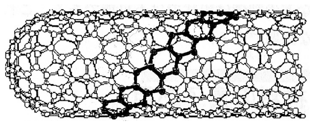


$C = na_1 + na_2$



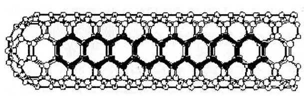
Zig-zag-type $(n, 0)$

- Metallic ($n = 3l$, $l = 1,2,3,\ldots$)
- Semiconductor ($n \neq 3l$)



Chiral-type (n, m)

- Metallic ($n - m = 3l$)
- Semiconductor ($n - m \neq 3l$)



Armchair-type (n, n)

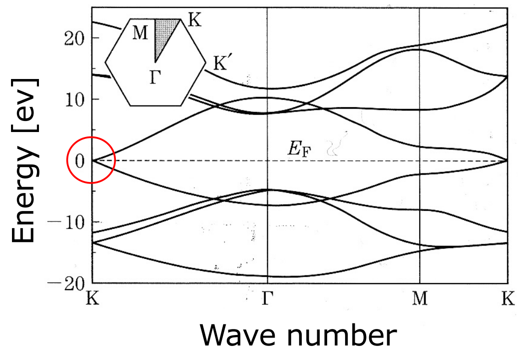
- Metallic

* http://www.wikipedia.org/

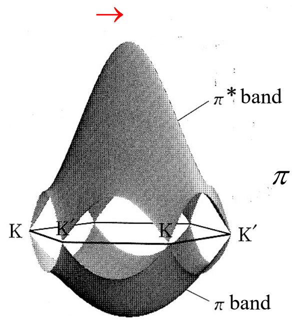
** H. Sakaki and N. Yokoyama, *Nanoelectronics* (Ohm-sha, Tokyo, 2004).

Band Structure of a CNT

Band structure results in both metallic and semiconductor characteristics :



2 bands cross at the Fermi level E_F.

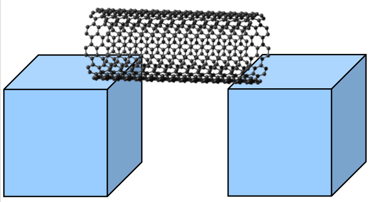
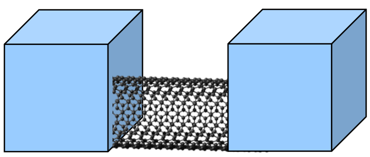
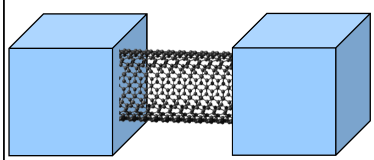


π band structure of graphene

* T. Ando and T. Nakanishi, *Carbon Nanotube and Quantum Effects* (Iwanami-shoten, Tokyo, 2007).

CNT Nanodevices

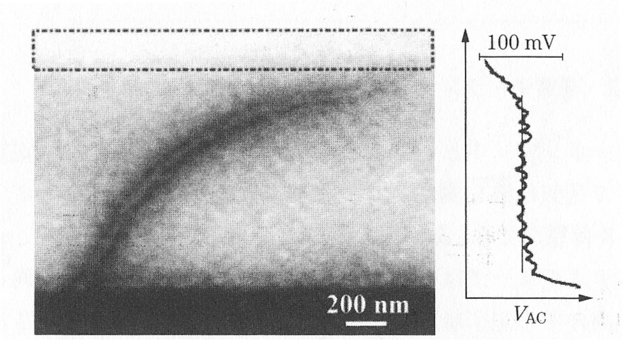
Three major configurations of CNT nanodevices :

Tube-on-metal	Metal-on-tube	Buried-tube
		
Fabrication processes : CNT dispersion Dielectrophoresis	Fine pattern process	Electrode melting
Contact resistance :		
CNT distortion Oxide barrier formation		

* http://www.suzukiylab.mp.es.osaka-u.ac.jp/document.html

Voltage distributions in a CNT

Localised charge imaging by a force microscopy : *



Transport properties are governed by contact resistance : **

Contact resistance > quantum resistance

→

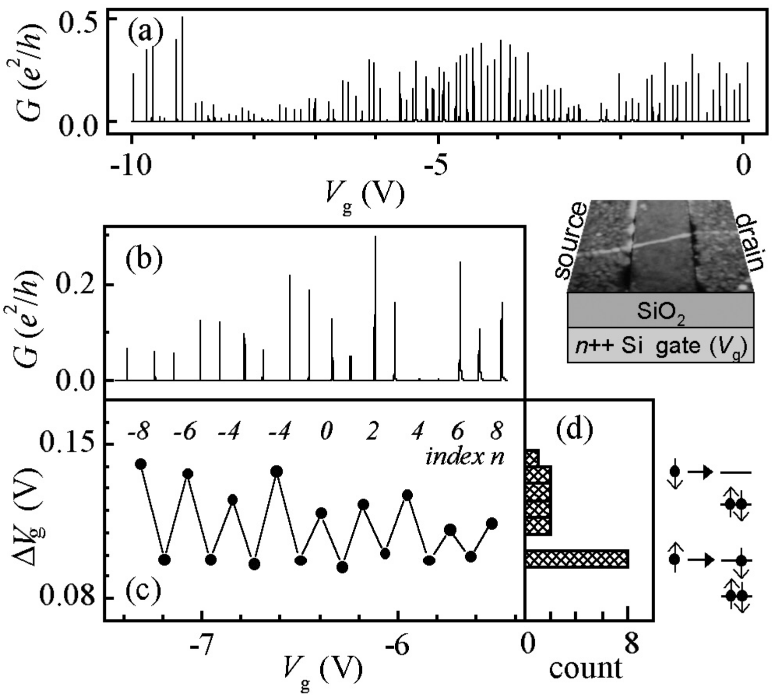
Contact resistance < quantum resistance

→

* A. Bachtold *et al.*, *Phys. Rev. Lett.* **84**, 6082 (2000).
** http://www.suzukiylab.mp.es.osaka-u.ac.jp/document.html

Coulomb Blockade in a CNT

Coulomb blockade was observed in a single-wall (SW) CNT :

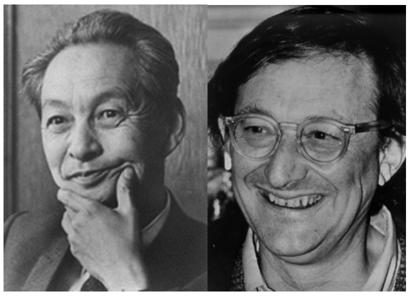


* D. H. Cobden and J. Nygård, *Phys. Rev. Lett.* **89**, 046803 (2002).

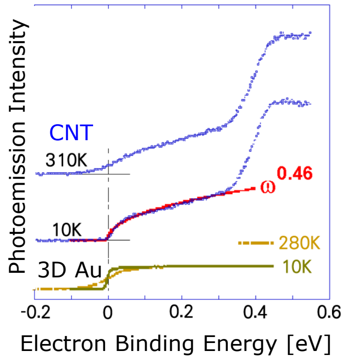
1D Electron Transport in a SW-CNT

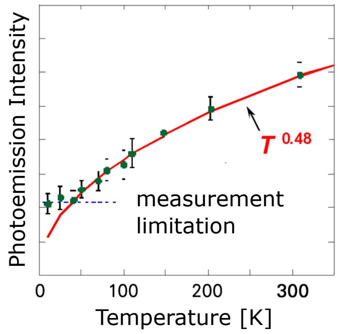
Tomonaga-Luttinger Liquid proposed in 1950 :

In most nanodevices, electrons behave as Fermi liquid :



In a 1D system, acceleration of 1 electron induces acceleration of a whole system ($\propto x^{\alpha}$; up to the Fermi velocity) :

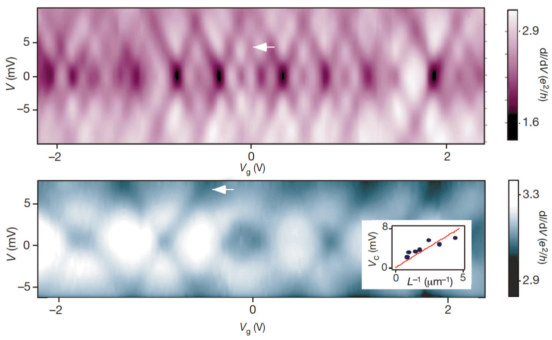


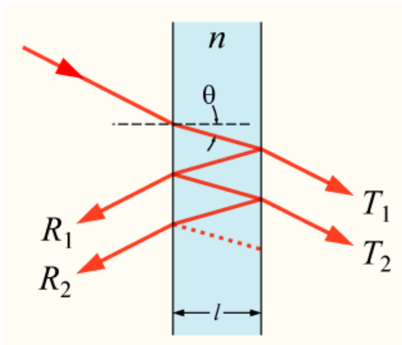


* http://www.wikipedia.org/; ** http://www.columbia.edu/
*** H. Ishii *et al.*, *Nature* **426**, 540 (2003).

Fabry-Perot Oscillation in a SW-CNT

Electron reflection at electrodes was observed in a CNT :

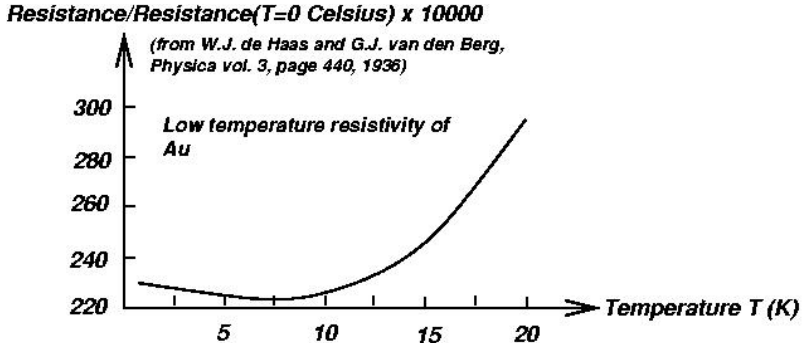




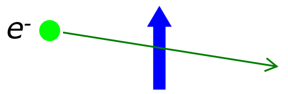
* W. Liang *et al.*, *Nature* **411**, 665 (2001).
** http://www.wikipedia.org/

Kondo Effect in a SW-CNT

In 1964, Jun Kondo proposed the Kondo effect :

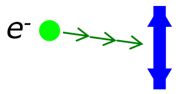


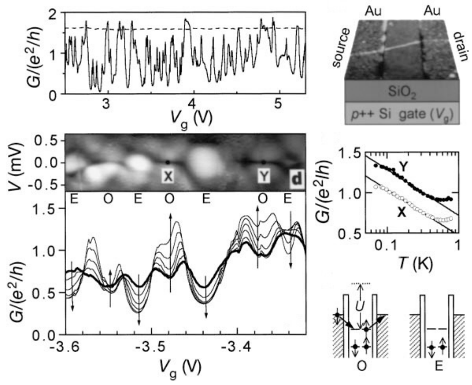
At high temperature :



magnetic impurity

At low temperature :

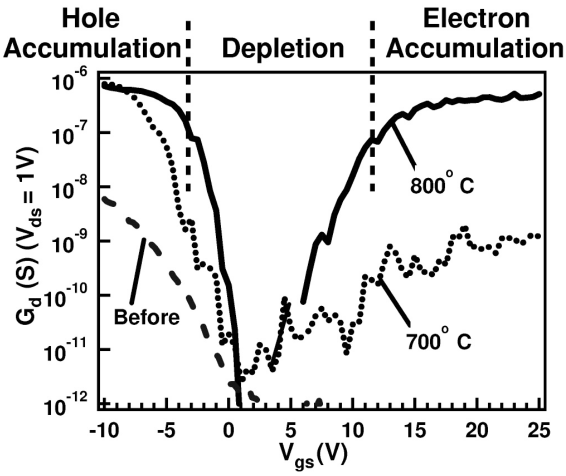




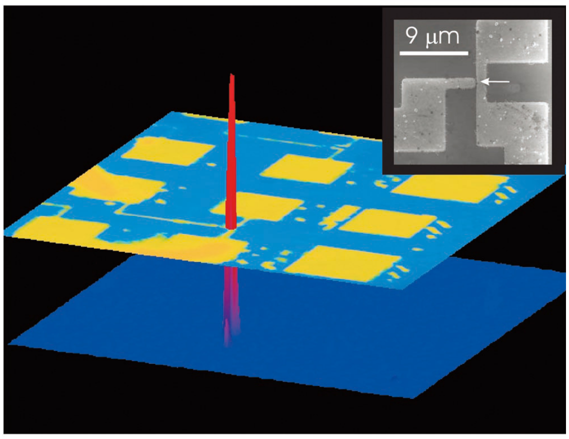
* http://www.aist.go.jp/
** http://www.wikipedia.org/
*** Jesper Nygård *et al.*, *Nature* **408**, 342 (2000).

Ambipolar Transport and Optical Emission in a SW-CNT

Ambipolar transport in a SW-CNT : *



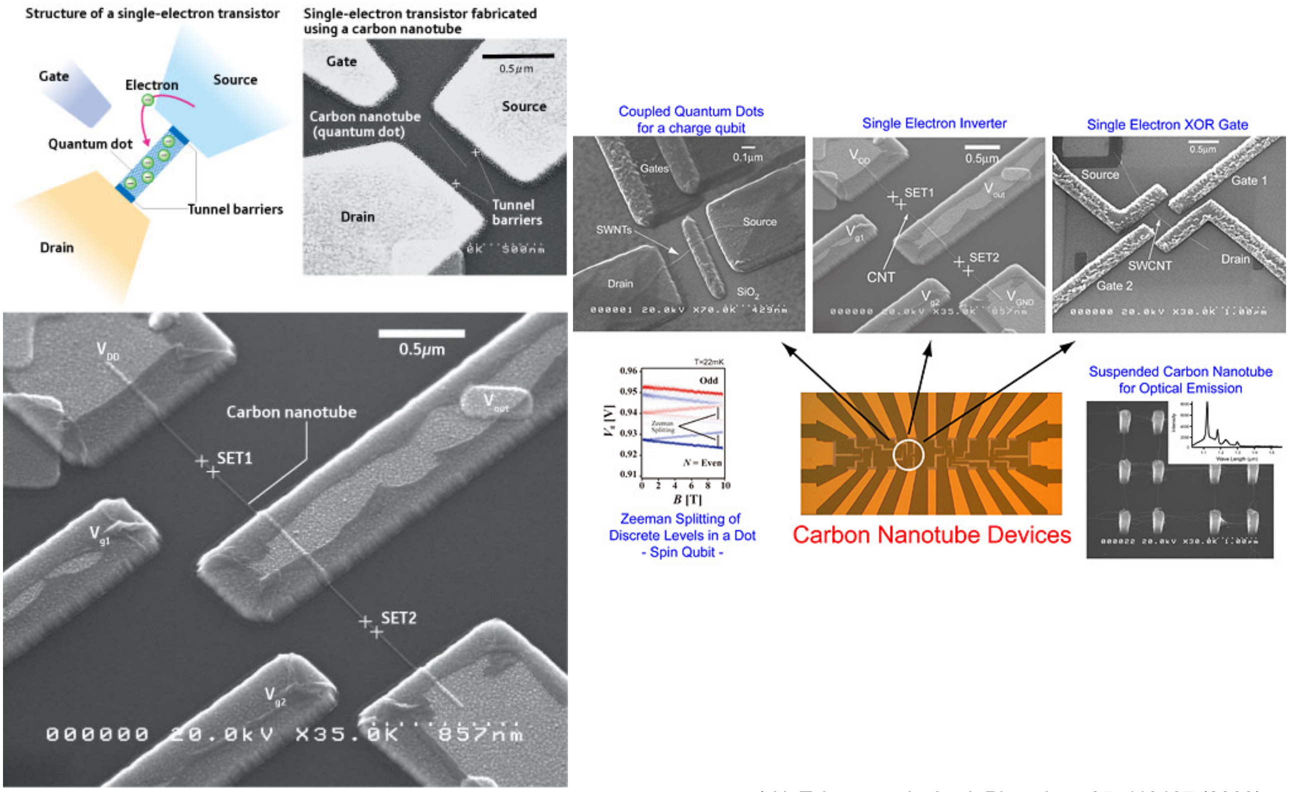
Optical emission from a SW-CNT : **



* R. Martel *et al.*, *Phys. Rev. Lett.* **87**, 256805 (2001).
** J. A. Misewich *et al.*, *Science* **300**, 783 (2003).

SET and THz Emission Demonstration with a CNT

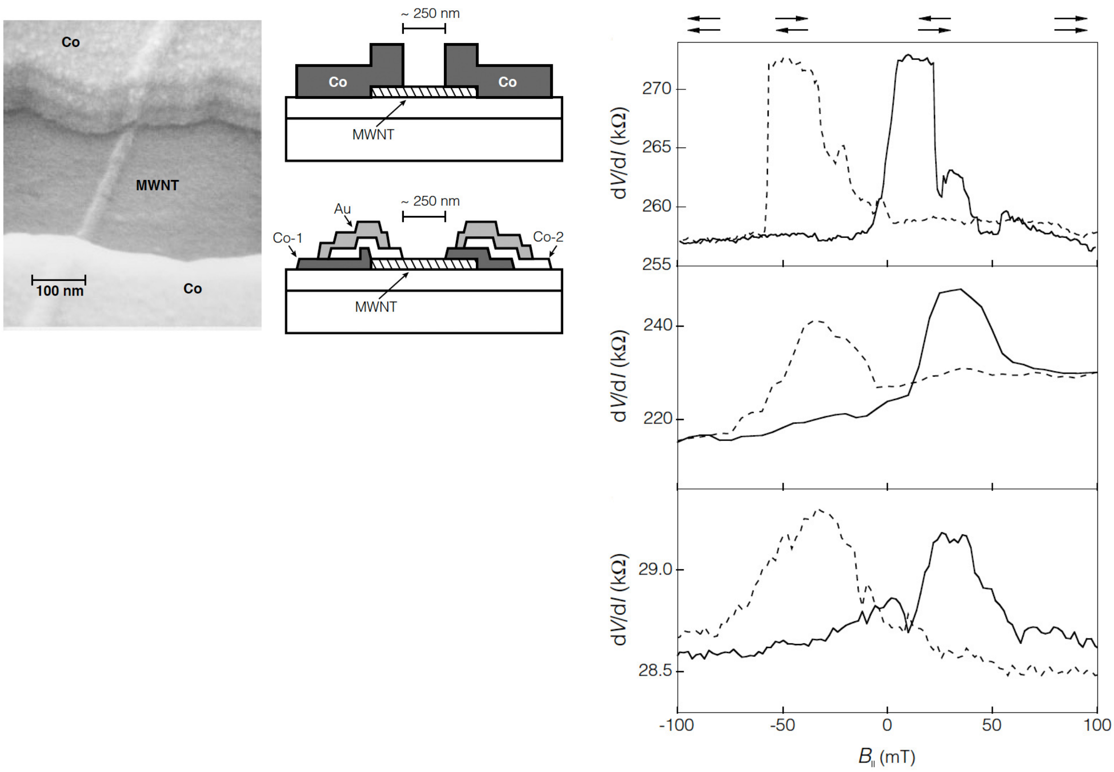
Single electron transistor (SET) consisting of a CNT :



* H. Tabata *et al.*, *Appl. Phys. Lett.* 95, 113107 (2009).

Spin Transport in a CNT

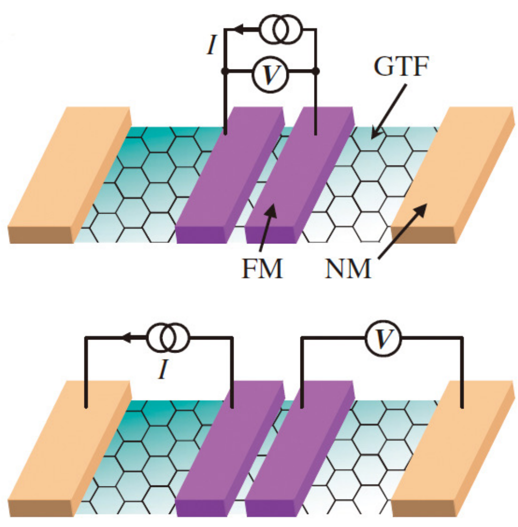
Magnetoresistance in a multi-wall (MW) CNT :

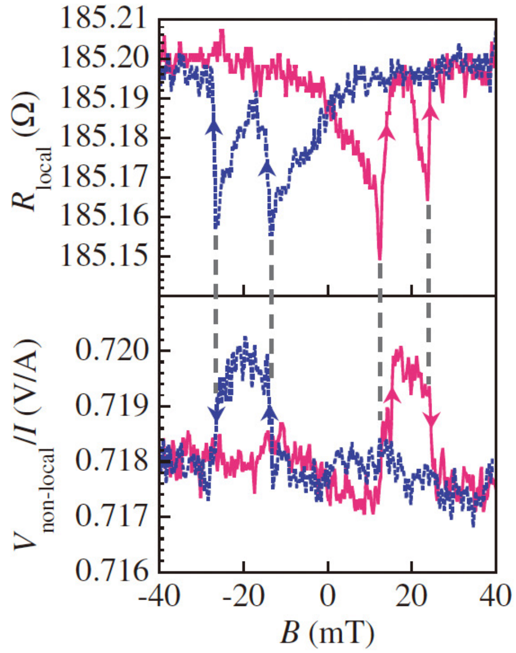


* K. Tsukagoshi *et al.*, *Nature* **401**, 572 (1999).

Spin Transport in Graphene

Spin transport in graphene at room temperature :





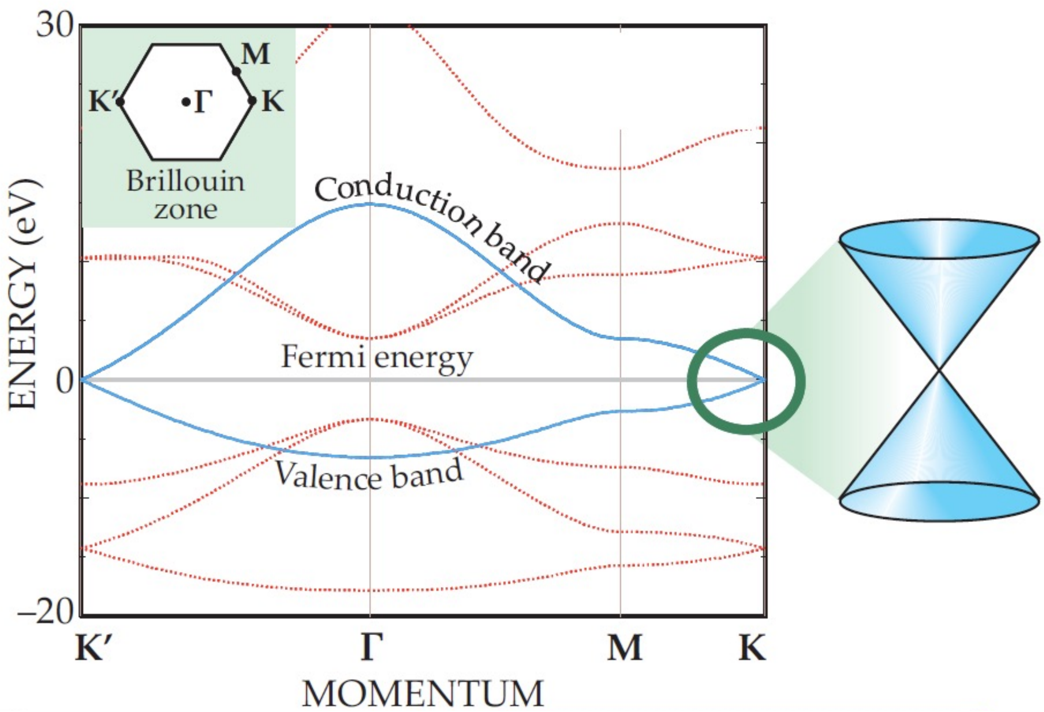
Spin transport signals

* M. Ohishi *et al.*, *Jpn. J. Appl. Phys.* **46**, L605 (2007).

Electron Transport in Graphene

Electron transport in graphene at room temperature :

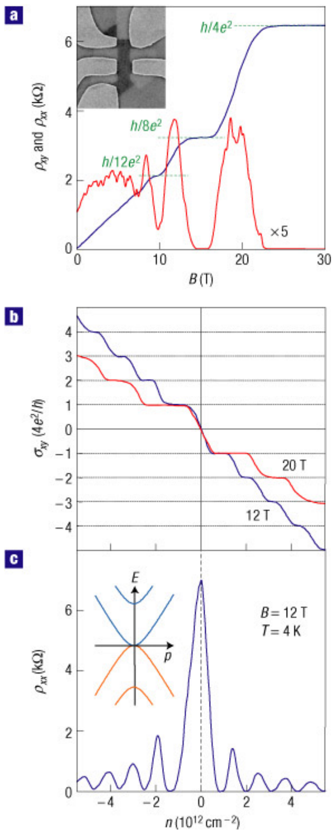
Mobility : 15,000 $cm^2V^{-1}s^{-1}$

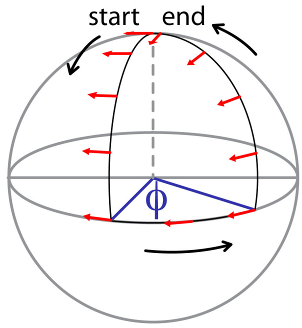


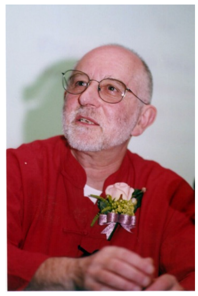
* A. K. Geim and A. H. MacDonald, *Phys. Today* **Aug.**, 35 (2007).

Berry's Phase in Graphene

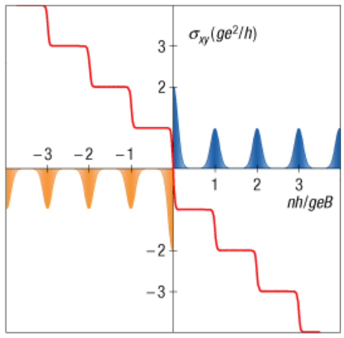
In 1984, Sir Michael V. Berry discovered a geometrical phase :







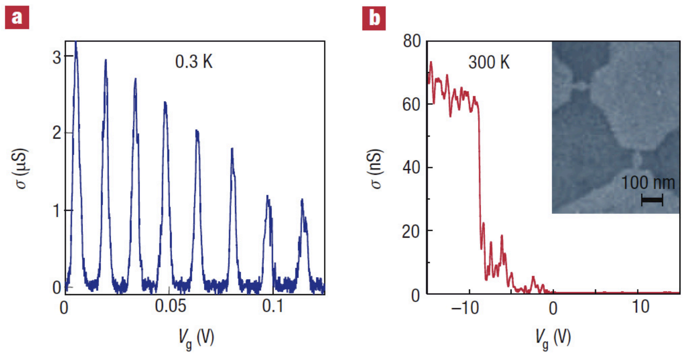
Quantum Hall effect in bilayer graphene



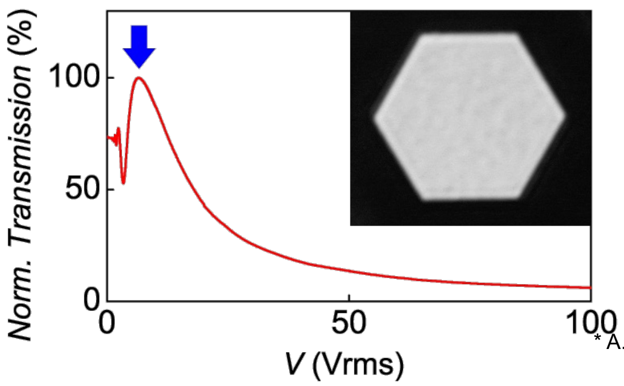
* http://www.phy.bris.ac.uk/people/Berry_mv/index.html
** http://www.qudev.ethz.ch/content/science/QuBerrySpecial.html
*** K. S. Novoselov *et al.*, *Natue Phys.* **2**, 177 (2006).

Transistors and Diodes using Graphene

Single electron transistor using graphene at room temperature :



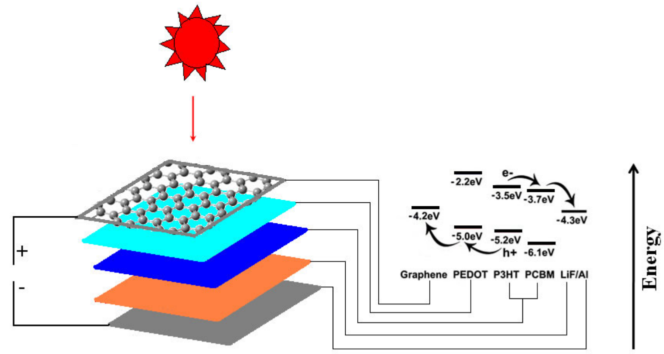
Liquid crystal device using graphene at room temperature :



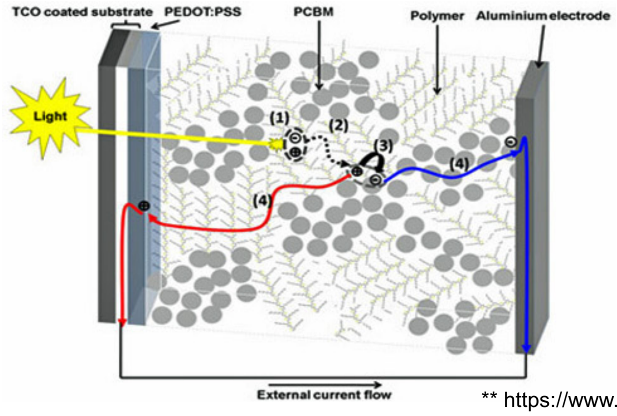
* A. K. Geim and K. S. Novoselov, *Nature Mater.* **6**, 183 (2007).
** http://www.condmat.physics.manchester.ac.uk/pictures/

Solar Cell using Graphene

Graphene-based solar cell :



Similar solar cell can be fabricated using fullerene :



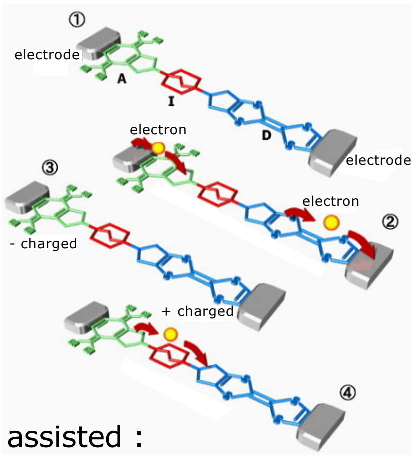
* http://www.mse.mtu.edu/faculty/yunhangh.html

** https://www.elitenetzwerk.bayern.de/ilkakriegel_organicsollarcell.0.html

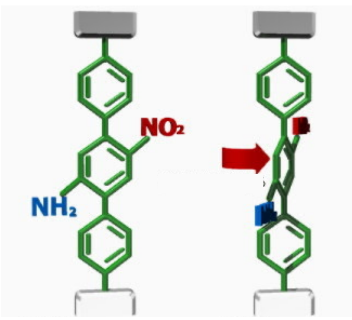
Molecular Diode

In 1974, A. Aviram and Mark A. Ratner proposed a molecular rectifier.

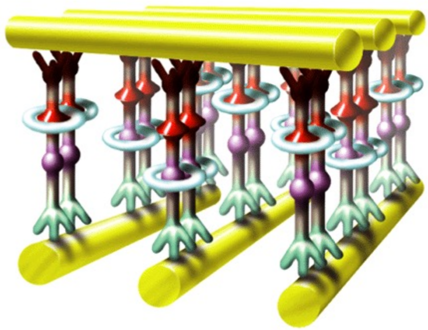
Langmuir-Blodgett (LB) films :



STM assisted :



Further integration :



* A. Aviram and M. A. Ratner, *Chem. Phys. Lett.* **29**, 277 (1974).

** http://www.s-graphics.co.jp/nanoelectronics/kaitai/moletronics/2.htm

*** R. F. Service, *Science* **294**, 2442 (2001).