Quick Review over the Last Lecture

Optical absorption:

Light emitting diode (LED):

Near-field optics:

(recombination)

Valence band
Conduction band
Direct transition starts
Indirect transition starts

Incident beam
Slit
Scattered light
Near-field light
Shield
I. Introduction to Nanoelectronics (01)
   01 Micro- or nano-electronics ?

II. Electromagnetism (02 & 03)
   02 Maxwell equations
   03 Scholar and vector potentials

III. Basics of quantum mechanics (04 ~ 06)
   04 History of quantum mechanics 1
   05 History of quantum mechanics 2
   06 Schrödinger equation

IV. Applications of quantum mechanics (07, 10, 11, 13 & 14)
   07 Quantum well
   10 Harmonic oscillator
   11 Magnetic spin
   13 Quantum statistics 1
   14 Quantum statistics 2

V. Nanodevices (08, 09, 12, 15 ~ 18)
   08 Tunnelling nanodevices
   09 Nanomeasurements
   12 Spintronic nanodevices
   15 Low-dimensional nanodevices
   16 Optical nanodevices
   17 Organic nanodevices

17 Organic Nanodevices

- Carbon nanotube
- Graphene
- 1D electron transport
Organic Materials

Organic materials include a carbon atom:


Diamond:

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

“Scotch tape method”

** [http://nobelprize.org/](http://nobelprize.org/)

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.
Discovery of a Carbon Nanotube


\[ C = n a_1 + n a_2 \]

** 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://nanocarb.meijo-u.ac.jp/jst/iijima.html
Band Structure of a CNT

Band structure results in both metallic and semiconductor characteristics:

[Image of band structure graph]

2 bands cross at the Fermi level $E_F$.

[Image of graphene band structure]


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CNT Nanodevices

Three major configurations of CNT nanodevices:

<table>
<thead>
<tr>
<th>Tube-on-metal</th>
<th>Metal-on-tube</th>
<th>Buried-tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Image of tube-on-metal configuration]</td>
<td>![Image of metal-on-tube configuration]</td>
<td>![Image of buried-tube configuration]</td>
</tr>
</tbody>
</table>

Fabrication processes:
- CNT dispersion
- Dielectrophoresis
- Fine pattern process
- Electrode melting

Contact resistance:
- Large
- Medium
- Small

CNT distortion
- Oxide barrier formation

* http://www.suzukiylab.mp.es.osaka-u.ac.jp/document.html
Localised charge imaging by a force microscopy:

Transport properties are governed by contact resistance:

Contact resistance $>\text{quantum resistance}$

Contact resistance $<\text{quantum resistance}$

Coulomb Blockade in a CNT

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


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

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 ($\propto x/a$; up to the Fermi velocity):

![Image](1D system example)


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Fabry-Perot Oscillation in a SW-CNT

Electron reflection at electrodes was observed in a CNT:

![Image](Fabry-Perot Oscillation)

** http://www.wikipedia.org/
In 1964, Jun Kondo proposed the Kondo effect:

At high temperature:

\[ e^- \rightarrow \text{magnetic impurity} \]

At low temperature:

\[ e^- \rightarrow \]

Ambipolar Transport and Optical Emission in a SW-CNT

Ambipolar transport in a SW-CNT:

\[ \text{Hole Accumulation} \quad \text{Depletion} \quad \text{Electron Accumulation} \]

Optical emission from a SW-CNT:

\[ \text{Optical emission from a SW-CNT} \]

\[ * \text{R. Martel et al., Phys. Rev. Lett. 87, 256805 (2001).} \]

\[ ** \text{J. A. Misewich et al., Science 300, 783 (2003).} \]
**SET and THz Emission Demonstration with a CNT**

Single electron transistor (SET) consisting of a CNT:


Spin Transport in a CNT

Magnetoresistance in a multi-wall (MW) CNT:

Spin Transport in Graphene

Spin transport in graphene at room temperature:

Local 2-terminal measurement

Non-local 4-terminal measurement

Anisotropic magnetoresistance (AMR)

Spin transport signals


Electron Transport in Graphene

Electron transport in graphene at room temperature:

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

Berry's Phase in Graphene

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

http://www.qudev.ethz.ch/content/science/QuBerrySpecial.html


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

Transistors and Diodes using Graphene

Single electron transistor using graphene at room temperature:

http://www.condmat.physics.manchester.ac.uk/pictures/

Liquid crystal device using graphene at room temperature:

** http://www.condmat.physics.manchester.ac.uk/pictures/
Solar Cell using Graphene

Graphene-based solar cell:

![Graphene-based solar cell diagram](image)

Similar solar cell can be fabricated using fullerene:

![Fullerene-based solar cell diagram](image)

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**Molecular Diode**

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

Langmuir-Blodgett (LB) films:

![Langmuir-Blodgett films diagram](image)

STM assisted:

![STM-assisted molecular rectifier](image)

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