02: Techniques for characterizing nanostructures

January 13, 2010
Announcements

- Please fill out the info sheet if you are new
- How many plan to take the GCC?
- No class next M (Jan/18)
Recap: nanoscale structures

- **Taxonomy**: nano-clusters, -wires, -tubes, sheets, heterostructures
  - 0D, 1D, 2D – how many degrees of freedom would you have if you were inside the structure?
  - Emphasis on structural diversity
  - We will see effects of size and shape on properties
CNT unit cell

### Periodic Table of Carbon Nanotubes

The semi-empirical bandgap $E_g$ is calculated according to H. Yorikawa and S. Murakami, Phys. Rev. B 52, 2723 (1995) for the semiconducting tubes (no curvature effects) and A. Kleiner and S. Egen, Phys. Rev. B 63, 073408 (2001) for the metallic and semi-metallic tubes (includes curvature). All other values are evaluated from the expressions below.

<table>
<thead>
<tr>
<th>$(n,m)$</th>
<th>$d_R$ (Å)</th>
<th>$E_g$ (eV)</th>
<th>$T$ ( Å)</th>
<th>$\theta$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$d$</th>
<th>$d_{H}$</th>
<th>$T$</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,0</td>
<td>0.79</td>
<td>3.48</td>
<td>4.29</td>
<td>90°</td>
<td>0.425</td>
<td>0.425</td>
<td>0.60</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1,1</td>
<td>1.20</td>
<td>2.61</td>
<td>4.46</td>
<td>90°</td>
<td>0.425</td>
<td>0.425</td>
<td>0.60</td>
<td>0.00</td>
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<td>0.0</td>
</tr>
<tr>
<td>2,1</td>
<td>1.71</td>
<td>1.54</td>
<td>4.65</td>
<td>90°</td>
<td>0.425</td>
<td>0.425</td>
<td>0.60</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3,1</td>
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<td>1.37</td>
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<td>0.425</td>
<td>0.425</td>
<td>0.60</td>
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<td>0.0</td>
</tr>
<tr>
<td>4,1</td>
<td>2.71</td>
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<td>4.99</td>
<td>90°</td>
<td>0.425</td>
<td>0.425</td>
<td>0.60</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5,1</td>
<td>3.21</td>
<td>1.03</td>
<td>5.10</td>
<td>90°</td>
<td>0.425</td>
<td>0.425</td>
<td>0.60</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6,1</td>
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<td>0.87</td>
<td>5.10</td>
<td>90°</td>
<td>0.425</td>
<td>0.425</td>
<td>0.60</td>
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<td>0.0</td>
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</tr>
<tr>
<td>7,1</td>
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<td>0.71</td>
<td>5.10</td>
<td>90°</td>
<td>0.425</td>
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<td>0.60</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Definitions:**
- $a$: length of unit vector
- $a_1$, $a_2$: unit vectors
- $b_1$, $b_2$: reciprocal unit vectors
- $C_b$: circumference of tube
- $d_R$: diameter of tube
- $\theta$: chiral angle
- $d$: highest common divisor of $(n,m)$
- $d_{H}$: highest common divisor of $(2n+m,2m+n)$
- $T$: translational vector of 1D unit cell
- $N$: number of atoms per 1D unit cell

### Carbon-Carbon Distance

- $d_{C-C} = 1.421$ Å (graphite)

### Expressions:

- $\alpha = \sqrt{3} \, a - C$:
- $\beta = \pi \, a - C$
- $r = \sqrt{\frac{3}{2}} \, a$
- $\theta = \frac{\pi}{6}$
- $\gamma = \frac{\sqrt{3}}{2}$

### Notes:

- The table presents values for different $(n,m)$ combinations, indicating the bandgap $E_g$, translation vector $T$, and number of atoms $N$ for various types of carbon nanotubes.

### Resources:

- Atomistix: www.atomistix.com
\(a_C - C\)  carbon–carbon distance  
\(a\)  length of unit vector  
\(\sqrt{3} a_C - C\)  
2.461 Å

\(a_1, a_2\)  unit vectors  
\(\frac{2\pi}{a} (\frac{1}{\sqrt{3}}, 1), \frac{2\pi}{a} (\frac{1}{\sqrt{3}}, -1)\)  in \((x, y)\) coordinates

\(b_1, b_2\)  reciprocal unit vectors  
\(\frac{2\pi}{a} (\frac{1}{\sqrt{3}}, 1), \frac{2\pi}{a} (\frac{1}{\sqrt{3}}, -1)\)  in \((x, y)\) coordinates

\(C_h\)  chiral vector  
\(na_1 + ma_2\)  \(n, m\) integer

\(L\)  circumference of tube  
\(L = |C_h| = a\sqrt{n^2 + m^2 + nm}\)  \(0 \leq m \leq n\)

\(d_t\)  diameter of tube  
\(d_t = \frac{L}{\pi}\)

\(\theta\)  chiral angle  
\(\tan \theta = \frac{\sqrt{3}m}{2n+m}\)  \(0^\circ \leq \theta \leq 30^\circ\)

\(d\)  highest common divisor of \((n, m)\)

\(d_R\)  highest common divisor of \((2n + m, 2m + n)\)  
\[d_R = \begin{cases} 
    d & \text{if } n - m \text{ is not a multiple of } 3d \\
    3d & \text{if } n - m \text{ is a multiple of } 3d 
\end{cases}\]

\(T\)  translational vector of 1D unit cell  
\[T = t_1 a_1 + t_2 a_2\]  \(t_1, t_2\) integer

\(t_1 = (2m + n)/d_R\)

\(t_2 = -(2n + m)/d_R\)

\(T\)  length of \(T\)  
\[T = \frac{\sqrt{3}L}{d_R}\]

\(N\)  number of atoms per 1D unit cell  
\[N = \frac{4(n^2 + m^2 + nm)}{d_R}\]  \(N/2 = \text{hexagons/unit cell}\)
What is the smallest CNT?

Hayashi et al., Nano Letters 3(7):887-889, 2003
Nanotube modeler

http://www.jcrystal.com/products/wincnt/
Today’s agenda

- Microscopy: techniques and limits
  - Optical
  - Electron
  - Scanning probe (AFM/STM)
- Surface/structural analysis: electron and X-ray techniques
- Optical spectroscopy
  - Raman
  - UV/visible light
  - Infrared

- This lecture could be an entire course (or more); our goal is to know the very basics of techniques we’ll refer to in later topics.
- We’ll overview how to measure properties in the coming lectures (mechanical, electrical, thermal, optical)
Today’s readings

Nominal: (on ctools)
- Binning, Quate, and Gerber, *Atomic Force Microscope*
- Rao, *Characterization of Nanomaterials by Physical Methods*

Extras: (on ctools)
- Several papers on dynamic characterization, e.g., time-resolved electron microscopy
Additional resources

- References listed on these slides
- Internet search!
- Review papers (in journals)
- Many good books, e.g.,
  - Grasserbauer and Werner (eds.), Analysis of Microelectronic Materials and Devices, ISBN 0471950130
- Courses at UM:
  - Structural and chemical characterization of materials, Prof. Steve Yalisove (MSE465 W10)
  - Experimental methods in solids, Prof. Samantha Daly (ME599 was offered in W09)
Calibration

1 micrometer = 10^{-6} \text{ m}
1 nanometer = 10^{-9} \text{ m}
1 angstrom = 10^{-10} \text{ m}

so...

1 \text{ mm} = 1,000,000 \mu\text{m}
1 \mu\text{m} = 1000 \text{ nm}
1 \text{ nm} = 10 \text{ Å}

http://www.sustainpack.com/nanotechnology.html
Resolution versus time

Red blood cells with white cell
~ 2-5 μm

DNA
~2-1/2 nm

5 Atoms of silicon
1 nm

1 nanometre (nm)
0.1 nm
0.01 μm
100 nm
1 μm
10 μm

Resolution (Å^{-1})

Electron Microscope

Light Microscope

Corrected EM

Haider (200keV)

Dietrich (200keV)

Marton

Ruska

Abbe

Amici

Ross

Year

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http://www.sustainpack.com/nanotechnology.html
What types of information do we want?

Chemical information

atomic

molecular

near-field optical

micro-IR micro-Raman

X-ray spectroscopy, tomography

electron microscopy

scanning probe microscopy

optical microscopy

Spatial resolution

1 nm

1 μm

1 mm

adapted from Park.com, A Practical Guide to Scanning Probe Microscopy
Optical microscope

Fig 2.2. The optical system of a microscope (using transmitted light) similar to that shown in Fig 2.3.
Limits of optical microscopy

- Diffraction limit defines spatial resolution, \( d = \frac{\lambda}{NA} \)
- Ability to fit spread (airy) function determines point-to-point resolution of ideal emitters

http://www.microscopyu.com/articles/formulas/images/resolutionfigure1.jpg
Limits of optical microscopy

- Ways to beat the diffraction limit
  - Immersion optics (e.g., increase NA)
  - Prior knowledge of what should be in the image
  - Surface and tip-enhanced methods
  - Use fluorescent beacons (e.g., quantum dots) to tag specific locations

Thomas J. Deerinck
National Center for Microscopy & Imaging Research
University of California - San Diego
La Jolla, California, USA
Quantum dot fluorescence image of mouse kidney section (240x)
Stochastic optical reconstruction microscopy (STORM)

Switchable fluorophores

Zhuang group at Harvard, [http://zhuang.harvard.edu/](http://zhuang.harvard.edu/)
Scanning electron microscope (SEM)

Figure 5.2 Schematic diagram showing the main components of a scanning electron microscope.
JEOL Conventional Tungsten High Vacuum SEMs

Ideal for failure analysis, inspection, and characterization.

### Available Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Resolution</th>
<th>Accelerating Voltage</th>
<th>Magnification</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSM-6390</td>
<td>3.0nm</td>
<td>0.5 to 30 kV</td>
<td>x5 to 300,000</td>
<td>X=125mm, Y=100mm</td>
</tr>
<tr>
<td>JSM-6390A</td>
<td>3.0nm</td>
<td>0.5 to 30 kV</td>
<td>x5 to 300,000</td>
<td>X=125mm, Y=100mm</td>
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<tr>
<td>JSM-6490</td>
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<td>0.3 to 30 kV</td>
<td>x5 to 300,000</td>
<td>X=125mm, Y=100mm</td>
</tr>
<tr>
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<td>x5 to 300,000</td>
<td>X=125mm, Y=100mm</td>
</tr>
</tbody>
</table>

http://www.jeol.com
SEM sample preparation

- Electrically conductive sample surface required
- Affix to sample stage with conductive tape (e.g., carbon) or conductive epoxy (e.g., polymer and Ag particles)
- Coat non-conductive samples with a thin metal layer (typically 10-100 nm), OR use environmental-SEM (E-SEM)
It's cold outside!

Nanometer Patterning with Ice

Gavin M. King,*† Gregor Schürmann,† Daniel Branton,† and Jene A. Golovchenko†§

Department of Physics, Department of Molecular and Cellular Biology, and Division of Engineering & Applied Sciences, Harvard University, Cambridge, Massachusetts 02138

Received March 3, 2005; Revised Manuscript Received April 12, 2005

device size, to enhance the role of quantum mechanical device characteristics, and to pattern increasingly complex substrates requires new lithographic approaches to define nanometer scale structures. Here we demonstrate a new approach to nanoscale e-beam patterning based on the condensation and beam stimulated sublimation of water ice, microscopy (SEM) and focused ion beam (FIB) apparatus (FEI Co., Hillsboro, Oregon). Subsequent exposure of the ice surface to focused energetic electron or gallium ion beams stimulates local removal of ice and ultimately exposes the underlying silicon substrate in whatever patterns the beams are configured to produce. After developing a broad...
Transmission electron microscope (SEM)

Figure 3.10. Ray diagram of a conventional transmission electron microscope (top path) and of a scanning transmission electron microscope (bottom path). The selected area electron diffraction (SAED) aperture (Ap) and the sample or specimen (Spec) are indicated, as well as the objective (Obj) and projector (Proj) or condenser (Cond) lenses. (Adapted from P. R. Buseck, J. M. Cowley, and L. Eyring, High-Resolution Transmission Electron Microscopy, Oxford Univ. Press, New York, 1988, p. 6.)
Helical microtubules of graphitic carbon

Sumio Iijima

NEC Corporation, Fundamental Research Laboratories.
# JEOL 200 kV Transmission Electron Microscopes

## Available Models

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<tr>
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<th>Magnification</th>
</tr>
</thead>
<tbody>
<tr>
<td>JEM-2100F</td>
<td>0.14nm Lattice</td>
<td>80 to 200 kV</td>
<td>x50 to 1,500,000</td>
</tr>
<tr>
<td>JEM-2100 LaB₆</td>
<td>0.10nm Lattice</td>
<td>80 to 200 kV</td>
<td>x50 to 1,500,000</td>
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<tr>
<td>JEM-2200FS</td>
<td>0.14nm Lattice</td>
<td>80 to 200 kV</td>
<td>x50 to 1,500,000</td>
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<tr>
<td>JEM-2500SE</td>
<td>STEM 0.2nm Lattice</td>
<td>80 to 200 kV</td>
<td>x100 to 20,000,000</td>
</tr>
<tr>
<td></td>
<td>TEM 0.14nm Lattice</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

http://www.jeol.com
Electron beam can damage a structure

Figure 4-22. Damage to a MWNT by electron beam exposure during TEM imaging (JEOL-2011 at 200 keV). Scales 5 nm.
TEM characterization of ZnO helices

TEM sample preparation

- Grid, typically 3 mm diameter
- Membrane (< 10 nm thick) often suspended over grid
- Fabricate thin sections by ion milling or microtoming

various online sources: e.g., Quantifoil, SPI
Sample prep using a focused ion beam (FIB)

Figure 9. Sample with feature of interest can be (a) cross sectioned in the FIB. The section can be advanced until desired feature appears or (b) it can be prepared for inspection in a TEM.

http://commons.wikimedia.org/wiki/Image:Fib_tem_sample.jpg
Lens aberrations determine the practical resolution limit

- It’s difficult to eliminate aberrations in metallic lenses

Rays focus at different points - due to non-uniformities in focusing fields, diffraction at apertures

*Fig. 1 (a) In a standard electron lens with spherical aberration, rays at different angles to the optic axis are brought to a focus at different points. (b) The effect of correcting the spherical aberration is to bring all rays into focus at the same point. The small blue area on the right of the lens represents the aberration disc.*
Aberration-corrected TEM can show individual atoms (0.1 nm resolution)

**Figure 2** Atomic arrangement of the Stone–Wales (SW) model. 

a, The SW transformation leading to the 5–7–7–5 defect, generated by rotating a C–C bond in a hexagonal network. 

b, HR-TEM image obtained for the atomic arrangement of the SW model. 

c, Simulated HR-TEM image for the model shown in b.

Environmental TEM (E-TEM) shows material dynamics
A sequence of images of the nucleation and subsequent growth of individual Cu crystallites during galvanic deposition at 5 mA/cm². The numbers in the upper right-hand corner indicate the number of seconds after the initiation of the current flow.
Scanning tunneling microscopy (STM)

- First to give real-space atomic resolution images
- ~10Å gap between conductive tip and conductive sample, using tunneling (exponential) current to measure displacement

“topografiner” invented by Young and colleagues, NIST, 1972
Binnig and Rohrer (IBM), Nobel Prize, 1986
STM: scanning modes

invented by Young and colleagues, NIST, 1972
Binnig and Rohrer, Nobel Prize, 1986
Figure from park.com, A practical guide to scanning probe microscopy
Quantum corral

Atomic force microscopy

invented by Young and colleagues, NIST, 1972
Binnig and Rohrer, Nobel Prize, 1986
Park.com, A practical guide to scanning probe microscopy
AFM image of graphite

http://www.physik.uni-augsburg.de/exp6/imagegallery/afmimages/afmimages_e.shtml
AFM cantilevers and tips

- Etched pyramids
- Oxide/etch sharpening
- Growth of nanostructured tips
Actuating single molecules using AFM

Lifting force

AFM cantilever

Tip

Linker

Molecule₂

Molecule₁

Support

Bond breaks at a certain force

AFM cantilever

Tip

Linker

Molecule₂

Molecule₁

Support

http://www.pitb.de/nolting/biophysics_methods/nanobiotech.html
http://www.veeco.com/pdfs/appnotes/AN92-BacterialAdhes_02176_rf_251.pdf

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High-speed (video-rate) AFM

- Key: resonant scanning in two axes

FIG. 1. A schematic of the HSAFM. The sample is mounted on a quartz crystal resonator that generates the fast scan axis and is driven in the orthogonal slow scan axis by a piezo actuator. An optical lever is used to measure the deflection of the microcantilever. An additional “direct force” is applied to the end of the cantilever, forcing the tip to maintain contact with the surface. By tuning the magnitude of the “direct force” and the degree of damping of the cantilever, a high bandwidth passive feedback loop is created.

http://www.infinitiesima.com/VideoAFM-download.html
http://www.s.kanazawa-u.ac.jp/phys/biophys/roadmap.htm
Structure determination using X-rays

Reciprocal space

Real space

X-ray scattering (diffraction)
Typical SAXS beamline

Scattering angles and feature sizes

Bragg’s law:

\[ \lambda = 2d \sin \theta \]

\[ q = \frac{2\pi}{d} \]

- Small-angle (SAXS): \(\sim 5-50\) nm
- Wide-angle (WAXS): smaller features than SAXS, to lattice spacing and below
- Ultra small-angle (USAXS): larger features than SAXS, e.g., structure-structure interactions
Diffraction rings $\rightarrow$ atomic spacings

Real space packing

Face centered cubic

Body centered cubic

Hexagonal

Reciprocal space image (unoriented domains)

Normalized peak positions

$\equiv 1; =\sqrt{4/3}; =\sqrt{8/3}$

$\equiv 1; =\sqrt{2}; =\sqrt{3}$

$\equiv 1; =\sqrt{3}; =\sqrt{4}$

Electron diffraction in TEM

The International Centre for Diffraction Data - ICDD - a non-profit scientific organization dedicated to collecting, editing, publishing, and distributing powder diffraction data for the identification of crystalline materials. The membership of the ICDD consists of worldwide representation from academe, government, and industry.

ICDD
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The 7th Pharmaceutical Powder X-ray Diffraction Symposium will be held in Orlando, FL, U.S.A.
Learn more @ www.icdd.com/ppxrd

ICDD Clinics on X-ray Powder Diffraction - Session I - Fundamentals of X-ray Powder Diffraction:
2-6 June 2008
Characterizing CNT forests by SAXS

(a) Monocapillary Synchrotron X-ray beam Focused X-ray beam Monocapillary
  Motorized capillary stage Motorized sample stage Flightpath (vacuum)
  CNT forest Scattered X-rays
  CCD

(b) Aligned Unaligned

Measuring CNT diameter using SAXS

\[ f(q, R_o) = \Delta \rho R_o \frac{2\{J_1(R_o q) - c J_1(c R_o q)\}}{q R_o (1 - c^2)} \]

\[ \frac{\pi/18}{-\pi/18} \int I(q, \theta) d\theta \]

\[ c = R_i/R_o \]

\[ T_s = 875^\circ C, D = 10.5 \text{ nm} \]

\[ T_s = 825^\circ C, D = 9.3 \text{ nm} \]

\[ T_s = 775^\circ C, D = 8.3 \text{ nm} \]

\[ T_s = 725^\circ C, D = 8.0 \text{ nm} \]

\[ T_s = 675^\circ C, D = 7.7 \text{ nm} \]

Grazing incidence SAXS (GI-SAXS)

Fig. 1. The principles behind GISAXS. \( k_i \) and \( k_f \) are the incident and scattered wave vectors, respectively, yielding the momentum transfer (i.e., the reciprocal space vector) \( q = k_f - k_i \). The angles \( \alpha_i \), \( \alpha_f \), and \( 2\theta \) are related to the components of the momentum transfer, either parallel (\( q_x \) and \( q_y \)) or perpendicular (\( q_z \)) to the sample surface, by the equations:

\[
q_x = |k_i|[\cos 2\theta \cos \alpha_f - \cos \alpha_i],
q_y = |k_i|[\sin 2\theta \cos \alpha_f],
q_z = |k_i|[-\sin \alpha_f + \sin \alpha_i].
\]

Close to the origin in reciprocal space because they are small, the in-plane and out-of-plane scattering angles, \( 2\theta \) and \( \alpha_f \), scale with the components \( q_y \) and \( q_z \) of \( q \). The sample can be rotated around its surface normal by an \( \omega \) rotation, which defines the orientation of the incident x-ray beam with respect to the in-plane crystallographic directions. A beam stop protects the bidimensional detector from the direct and reflected beams.
Grazing incidence SAXS (GI-SAXS)

Chemical analysis

- **X-ray photoelectron spectroscopy (XPS)** $\rightarrow$ compounds
  - X-rays in, electrons out

- **Energy-dispersive X-ray spectroscopy** $\rightarrow$ elements
  - Electrons in, X-rays out

- **Auger electron spectroscopy** $\rightarrow$ elements
  - Electrons in, electrons out

- **Optical spectroscopy**: peak $\rightarrow$ vibrational mode
  - Resonant Raman spectrometry
  - IR spectroscopy

- Mobility-based measurements of gases and liquids, e.g., mass spectrometry

- **Electron and X-ray techniques** = VACUUM
- **Optical techniques** = AMBIENT
Lateral resolution vs. depth resolution

Depth Resolution/Sampling Depth

Lateral Spatial Resolution

Thin/Tapered specimens
Thick/Flat specimens

AP FIM
SIMS LMMS
ISS XPS
TXRF
RBS
NDP PGNP
UV/V-FM 
µRaman
FTIR
XRF, XRD
SEM/EPMA
EDS/WDS
X-ray
AEM EELS
AEM X-ray
NSOM
AP FIM

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X-ray photoelectron spectroscopy (XPS)

Photo-Emitted Electrons (< 1.5 kV) escape only from the very top surface (70 - 110Å) of the sample.

 Electron Energy Analyzer (0-1.5kV) measures kinetic energy of electrons.

Electron Detector counts the electrons.

Focused Beam of X-rays (1.5 kV)

SiO₂ / Si° Sample

Samples are usually solid because XPS requires ultra-high vacuum (<10⁻⁶ torr).

Si (2p) XPS signals from a Silicon Wafer

Output used to determine material

$E_{binding} = E_{photon} - E_{kinetic} - \phi$

X-rays in

Measured

Work function of spectrometer (calibrated)


Work function of the spectrometer: http://www.rikenkeiki.com/pages/AC2.htm

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XPS

Is the CNT growth catalyst metal or oxide?

metallic Fe on Al$_2$O$_3$

Fe-oxide on Al$_2$O$_3$

Figure 3. SEM images after CVD onto substrates with Al$_2$O$_3$ buffer layers. (a) CVD performed without previous O$_2$ plasma treatment; (b) CVD performed after O$_2$ plasma treatment. Scale bars are 100 nm.
Infrared (IR) spectrometry

Infrared (IR) spectrometry

Wavelength
μ = 10^{-6} meter

Note inverted peaks
Top: 100% transmission
Bottom: No transmission

Frequency
cm^{-1} = Hz/c

vanillin
(CCl_4 solution)

http://www.cem.msu.edu/~reusch/VirtualText/Spectrpy/InfraRed/infrared.htm
Raman spectroscopy

- Raman shift: scattered light shifts in frequency when it excites a molecular vibration; tuning this excitation to an electronic transition in the sample gives a huge enhancement.
Raman spectroscopy of CNTs

Ordinal Comparisons:

G/D Ratio = CNT quality

G/Si Ratio = CNT yield

D-band = Defects in CNTs and defective carbon on substrate

Raman peak of a SWNT shifts with strain ...like a guitar string

FIG. 3. (Color online) (a) 2D integrated intensity map of the silicon peak at 520 cm\(^{-1}\). The dark regions correspond to the trench regions. (b) 2D integrated intensity map of the \(G\) band between 1500 and 1600 cm\(^{-1}\) taken from a SWCNT in the same region as in (a). (c) Actual \(G\)-band spectra along the length of the SWCNT shown in (b). The peak frequency of the most intense peak is observed to shift linearly with respect to the position on the substrate and remains constant across the trenches.

How were these pictures taken?

Nanoclusters
Magic #’s of atoms ≤1 nm size

Nanoparticles
100’ s-1000’ s of atoms
~1-100 nm diameter

Nanowires
Filled
~1-100 nm dia, up to mm long and beyond!

Nanotubes
Hollow

Nanosheets
~1 atom thick
Characterization facilities at UM

Electron Microbeam Analysis Laboratory (EMAL)
http://www.emal.engin.umich.edu/
Facilities: Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM), X-ray Photo-electron Spectroscopy (XPS), Focused Ion Beam (FIB), and others.

X-Ray MicroAnalysis Laboratory (XMAL)
http://www.mse.engin.umich.edu/research/xmal
Facilities: X-ray Diffraction and X-ray Scattering

Michigan Ion Beam Laboratory (MIBL)
http://www-ners.engin.umich.edu/research/Mibl/index.html
Facilities: Rutherford Backscattering Spectroscopy, Ion Implantation