Probing the underlying physics of nanoelectronics with Raman spectroscopy

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New Group Formed at NIST

Lead by Curt Richter

NANOELECTRONICS GROUP (683.04)

Conducts basic research to advance the optical and electrical measurement science infrastructure necessary for innovation in future nanoelectronic and thin-film devices, and their component materials.

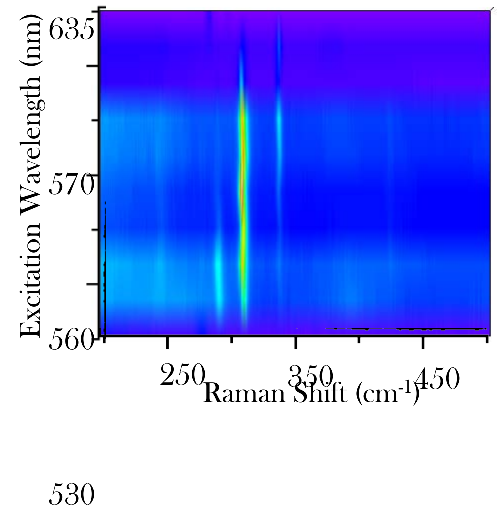
- **Pushes the frontiers of optical spectroscopies** (e.g., Raman spectroscopy, spectroscopic ellipsometry, and infrared spectroscopy) **and electrical measurements** (e.g., magnetotransport, nanoelectronic test structure development, and temperature dependent current-voltage spectroscopy)

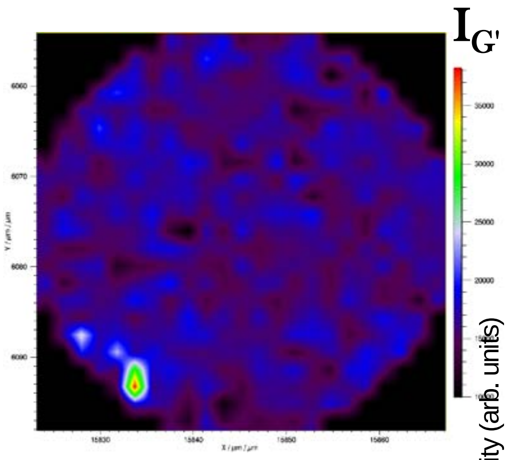
- **Develops and advances novel measurements that combine and correlate optical and electrical methods** such as internal photoemission, magneto-optical spectroscopy, and transient photocurrent spectroscopy.

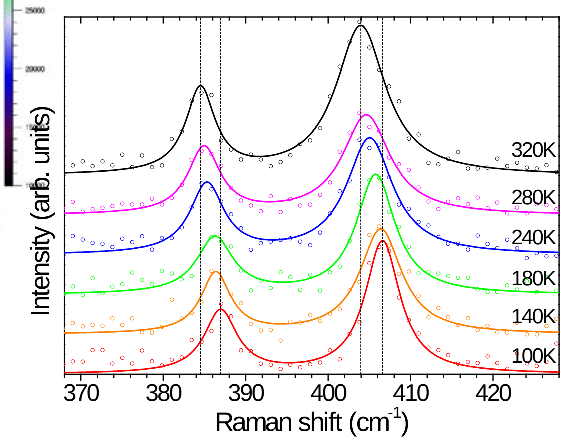
Outline

Raman spectroscopy applied to

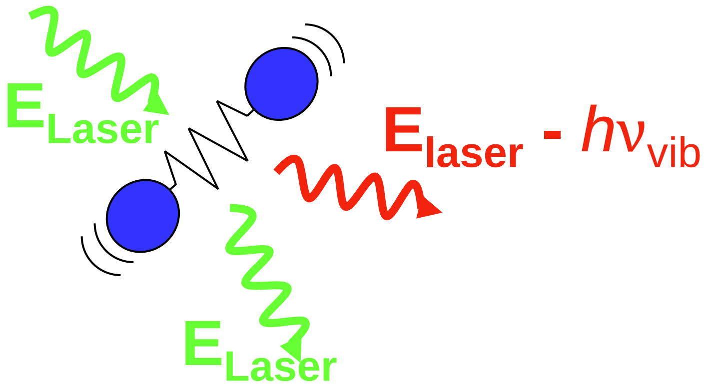
- Carbon Nanotubes
- 2D Materials
  - Graphene
  - MoS_2

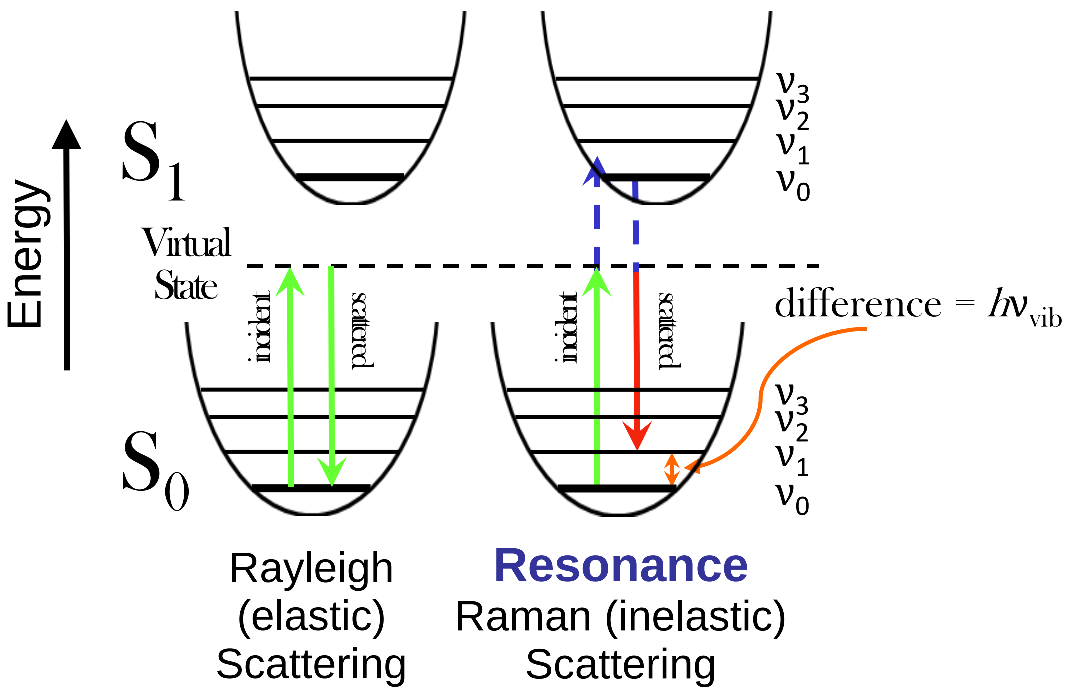






The Raman Effect: Inelastic Scattering

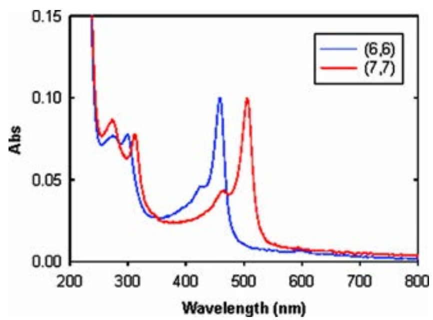


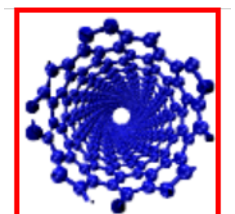


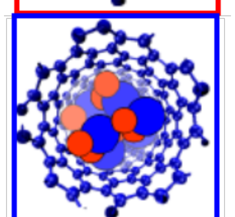
- Rapid
- Highly specific
- Non-destructive
- Rich
    - Layer number and orientation
    - Defects/Edges
    - Electron Phonon coupling
    - Temperature
    - Doping
    - Strain
    - Crystallographic orientation
    - Chemical functionalization

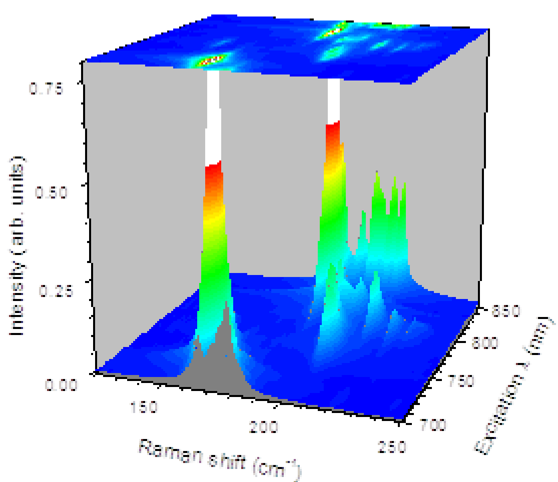
Novel Measurement Methods

- Techniques enhanced by presence of the nano-object
- Very sensitive to carbon nanostructures, i.e. carbon nanotubes and graphene
- Unique capabilities spanning THz through NIR region









Expertise and Resources

- Raman Spectroscopy
  - Triple-grating XY-800
  - Renishaw InVia Microscope
- Laser fluorescence spectroscopy
- Combined AFM-Raman imaging
- Surface-enhanced Raman spectroscopy (SERS)
- Tip-enhanced Raman spectroscopy (TERS)
- Multiple laser excitation

  Argon ion (multiple discrete lines), Ti:Sapphire (tunable), 633 nm HeNe, 785 nm diode, Dye lasers (tunable)
- Cryostats : 4 K – 400 K
- Environmental cell

ACS Nano 2011 5, 5 3943

J. Am. Chem. Soc., 2011, 133 (33), pp 12998–13001

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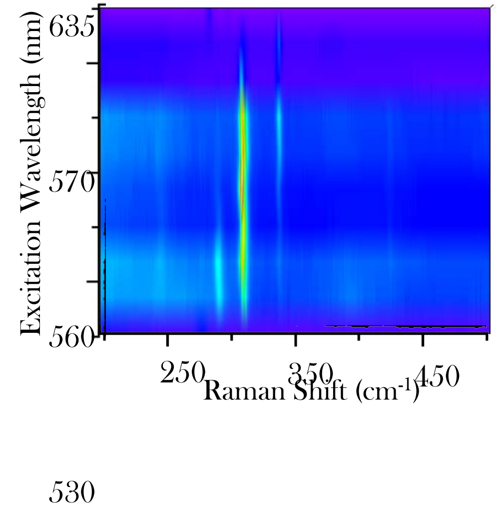
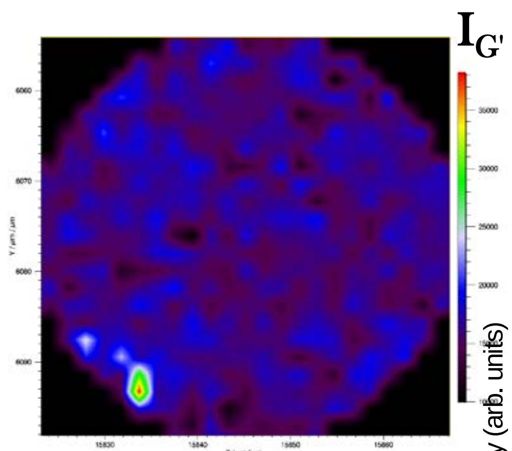
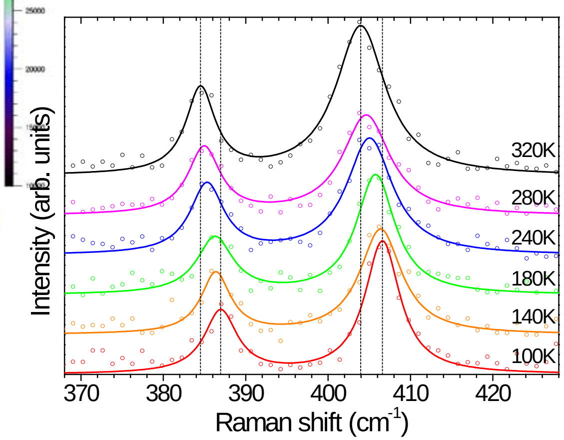
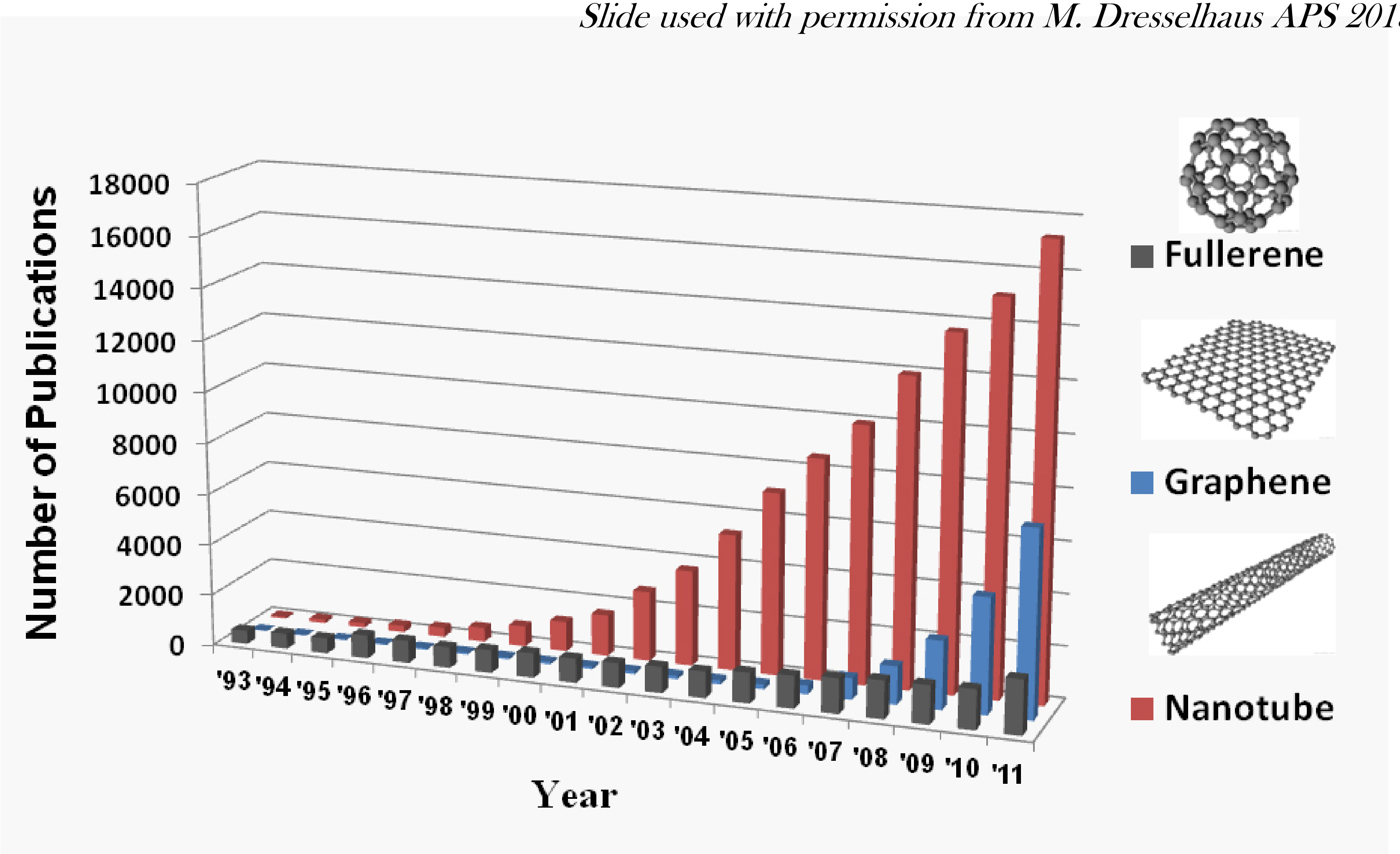






Publications per year

Slide used with permission from M. Dresselhaus APS 2013



Data extracted from the Web of Knowledge (Science Citation Index) searching for the words fullerene, nanotube, and graphene.

Nanoeletronics

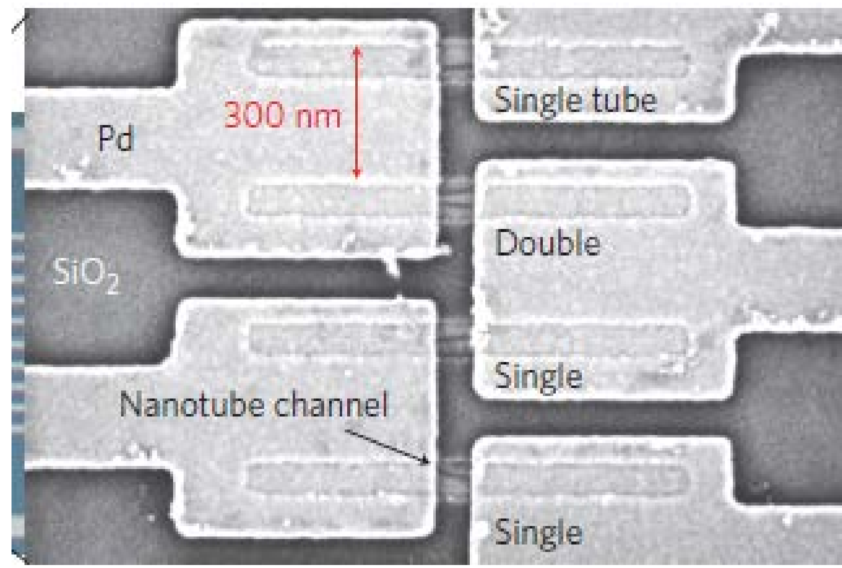
nature nanotechnology

LETTERS

PUBLISHED ONLINE: 28 OCTOBER 2012 | DOI: 10.1038/NNANO.2012.189

High-density integration of carbon nanotubes via chemical self-assembly

Hongsik Park*, Ali Afzali*, Shu-Jen Han, George S. Tulevski, Aaron D. Franklin, Jerry Tersoff, James B. Hannon and Wilfried Haensch



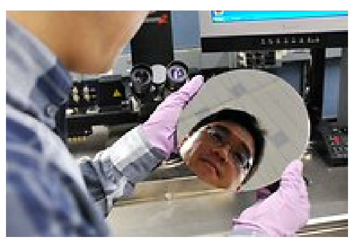
Bits

OCTOBER 28, 2012, 2:00 PM | 45 Comments

I.B.M. Reports Nanotube Chip Breakthrough

By JOHN MARKOFF

SAN FRANCISCO — I.B.M. scientists are reporting progress in a chip-making technology that is likely to ensure that the basic digital switch at the heart of modern microchips will continue to shrink for more than a decade.



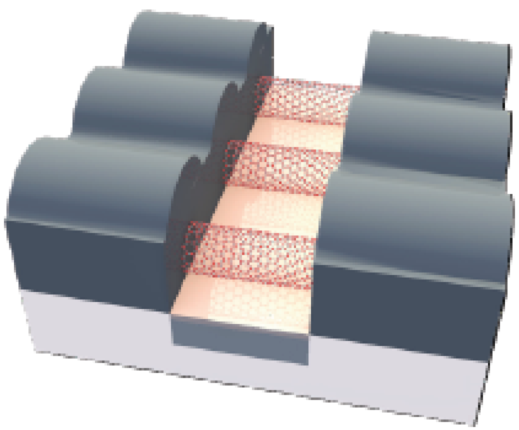
I.B.M. Research

The face of an I.B.M. research scientist, Hongsik Park, is reflected in a wafer used to make microprocessors.

The advance, first described in the journal Nature Nanotechnology on Sunday, is based on carbon nanotubes — exotic molecules that have long held out promise as an alternative to silicon from which to create the tiny logic gates now used by the billions to create microprocessors and memory

Recent Workshop

Carbon NanoTube Digital Electronics WORKSHOP



Purpose:
To review and discuss the current status and potential benefits of carbon nanotubes in digital electronic applications.

Who will attend (invitation only):
- Top researchers in the field from academia, government, and industry.
- Program managers and other colleagues from relevant government agencies.

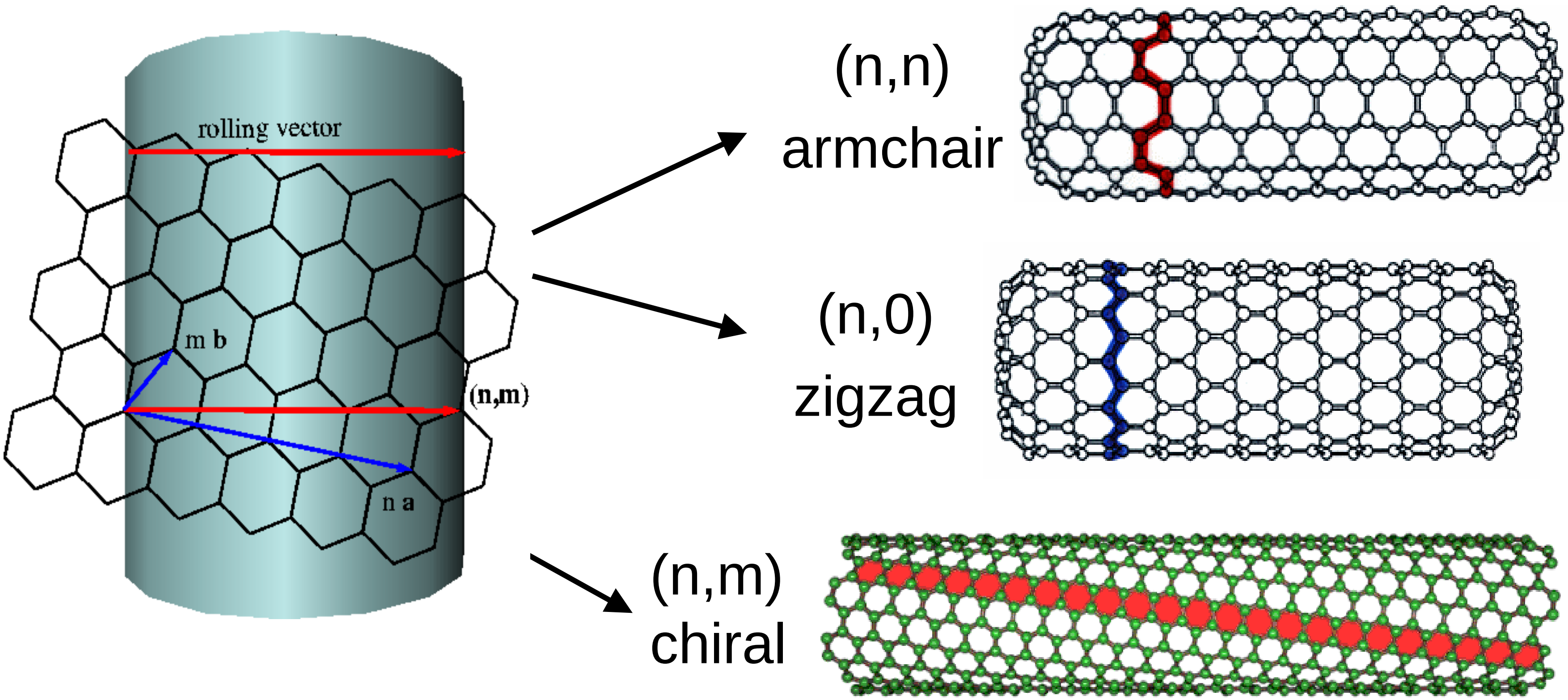
Date:
Thursday, September 6, 2012

Location:
NIST
100 Bureau Drive
Gaithersburg, MD 20899

Registration:
http://www.nist.gov/pml/div683/cnt_workshop.cfm
No registration fees
Coffee and lunch provided

Lodging:
Block of rooms reserved for 9/5 and 9/6 at Hilton

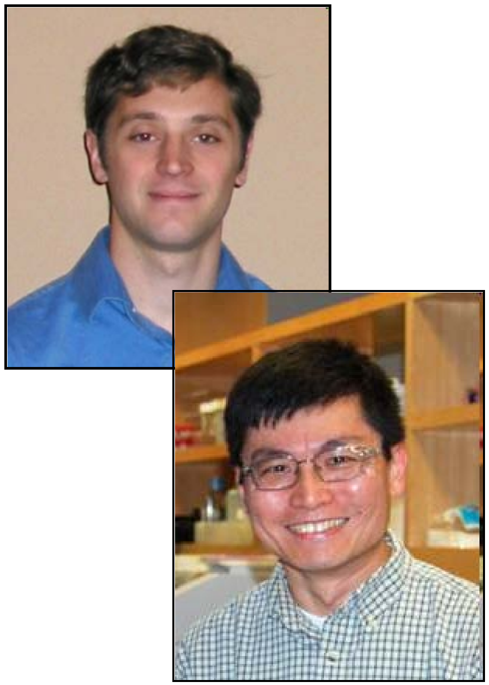
Single-Wall Carbon Nanotubes



Roll up vector determines physical properties, electronic nature and surface interactions.

NIST SWCNT Team

Fundamental Metrology for Carbon Nanotube Science and Technology



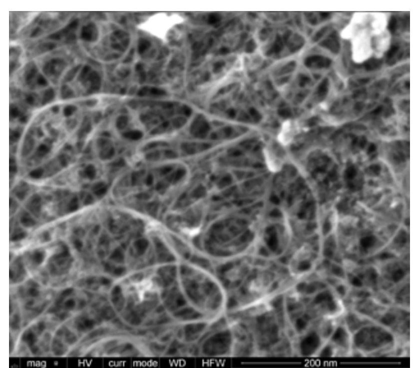
Identify the fundamental properties of the nanomaterials

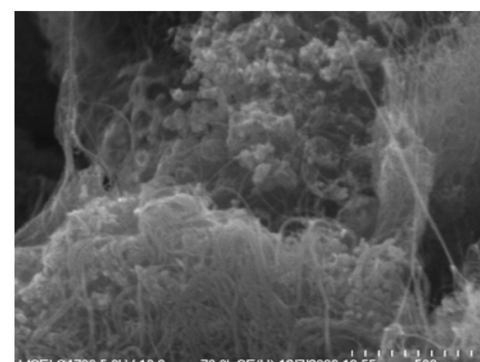
Isolate the nanomaterial for study

Polydispersity Problem

ALL SAMPLES are DIFFERENT

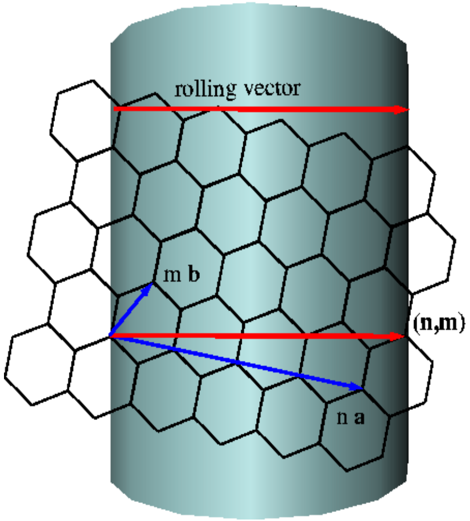
SWCNT length distribution, powder morphology, impurity content all vary batch to batch (or even within a batch) and across manufacturers.



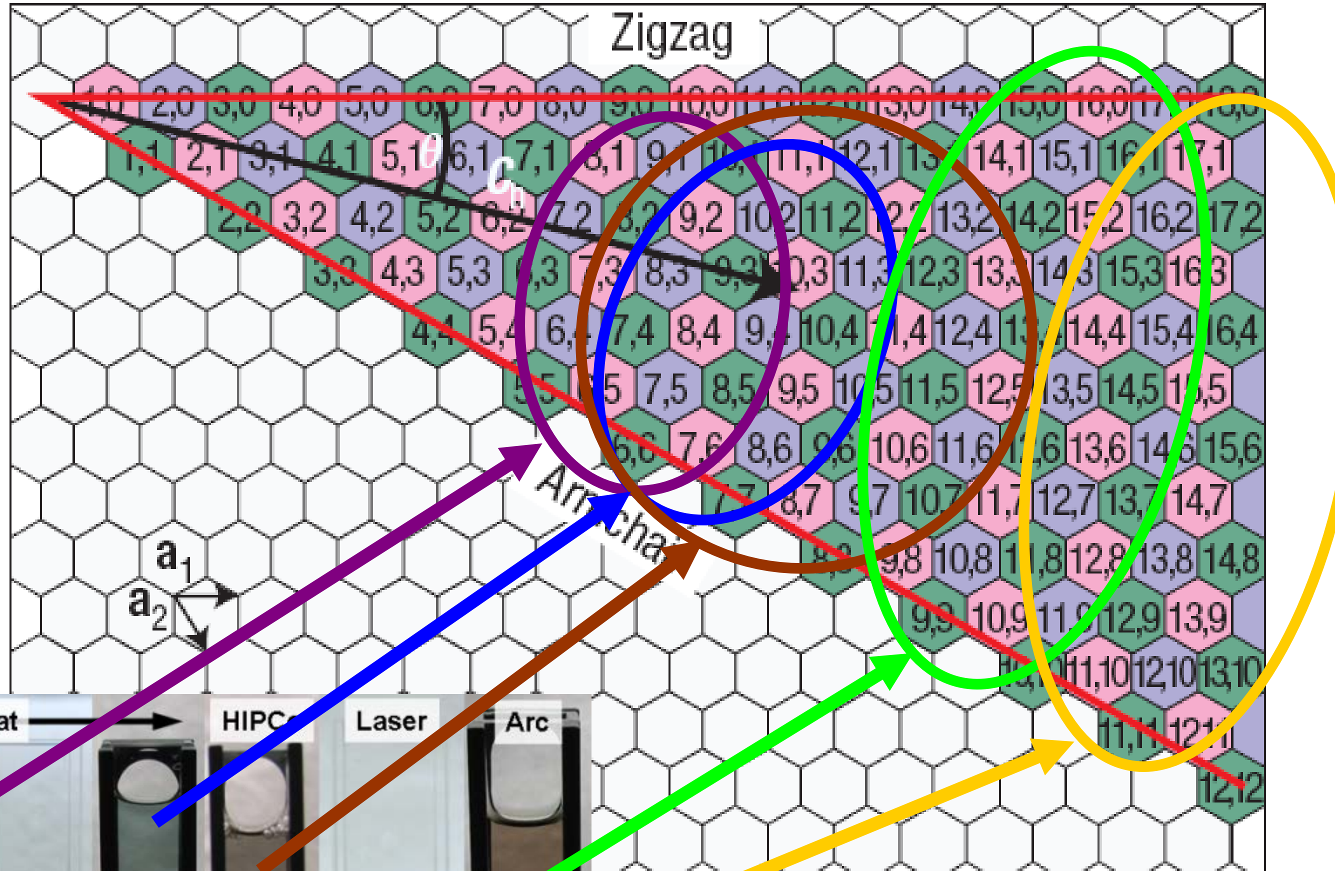


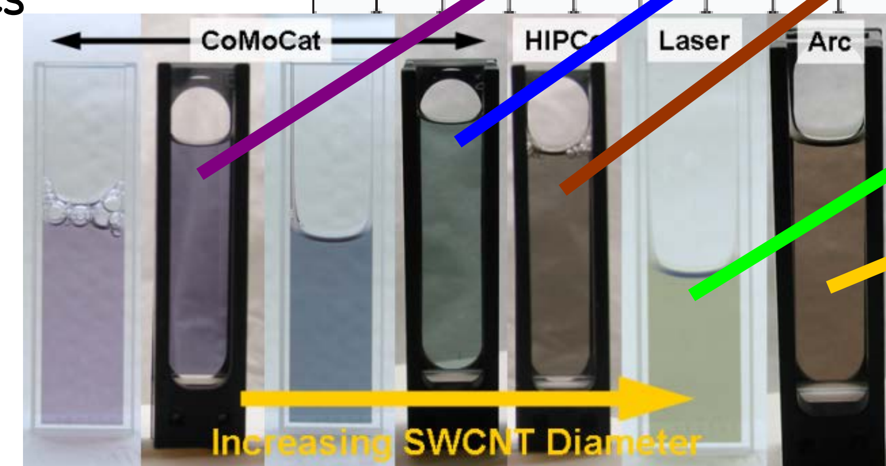
Polydispersity

Synthesis techniques produce varying SWCNT distributions



chiral vector determines physical properties





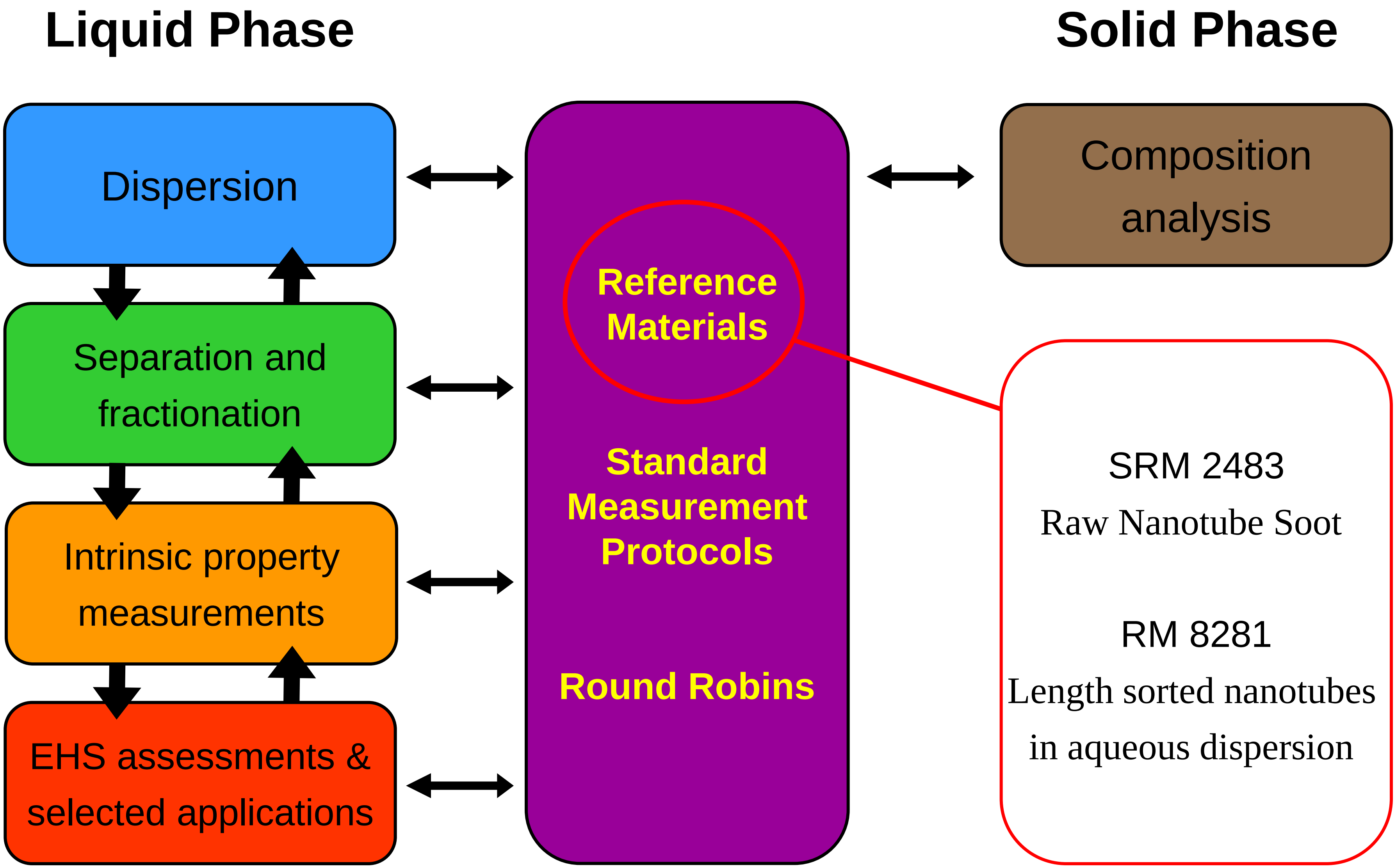
Hersam *et al.*, *Nature Nanotech* 2008

green: metallic;

Pink, Purple: Semi-conducting

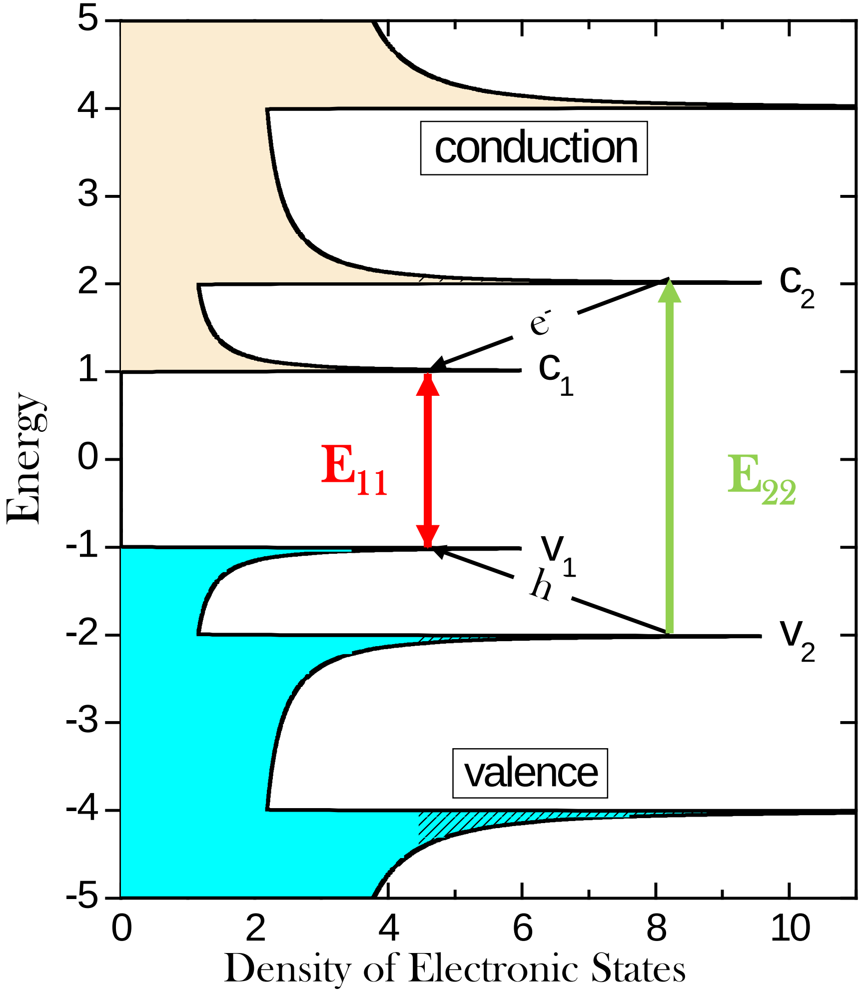
NIST

Nanotube Metrology Program

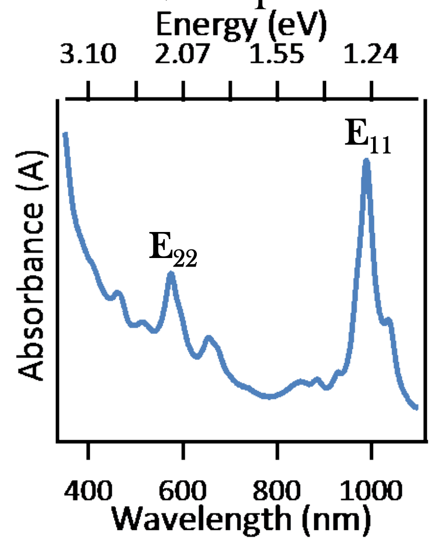


Optical Properties of SWCNTs

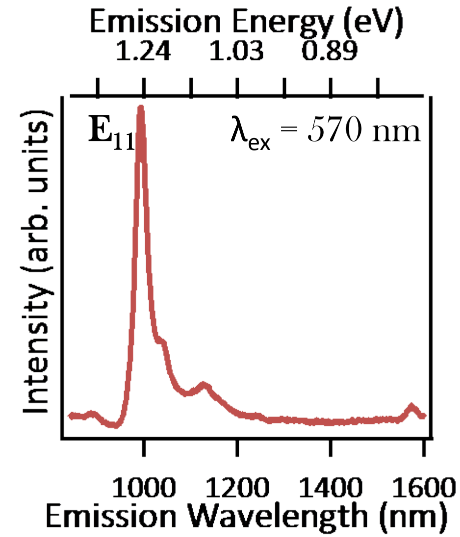
Optical properties of SWCNTs arise from van Hove singularities in 1-D density of states



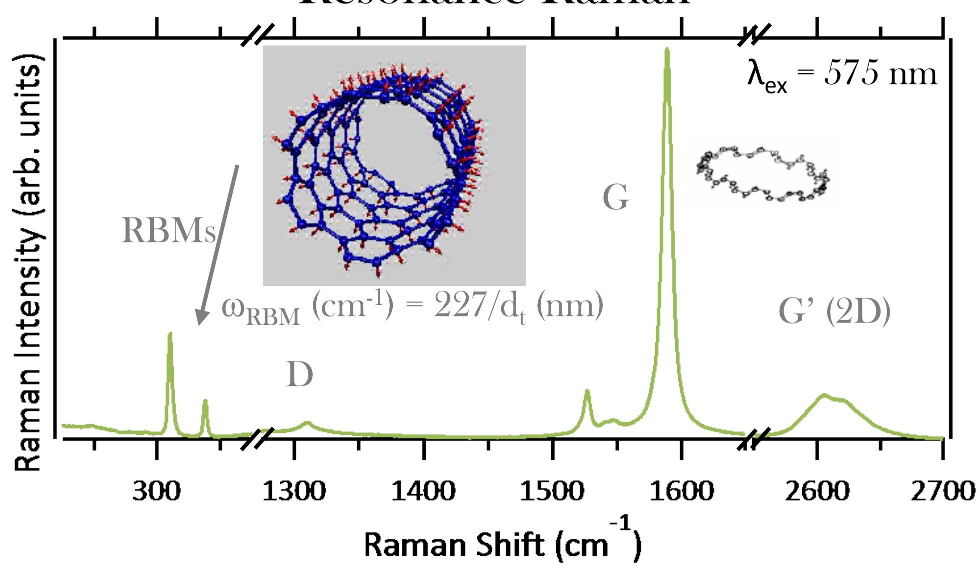
Absorption



Photoluminescence



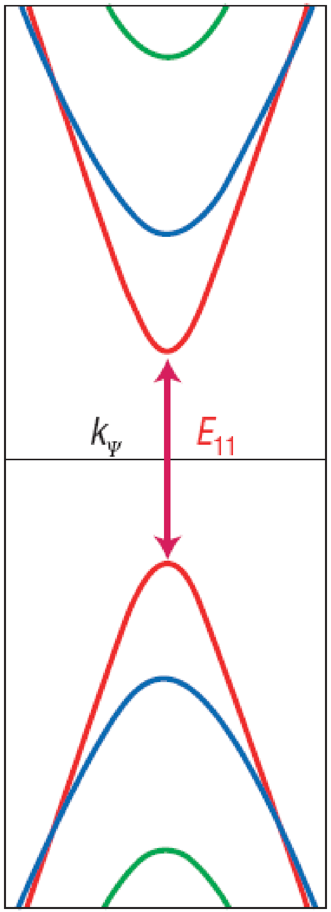
Resonance Raman

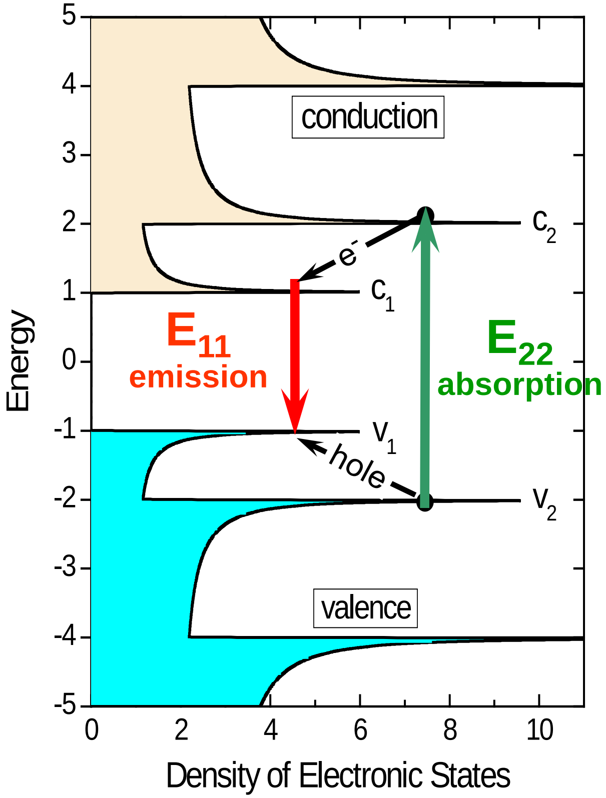


NIST

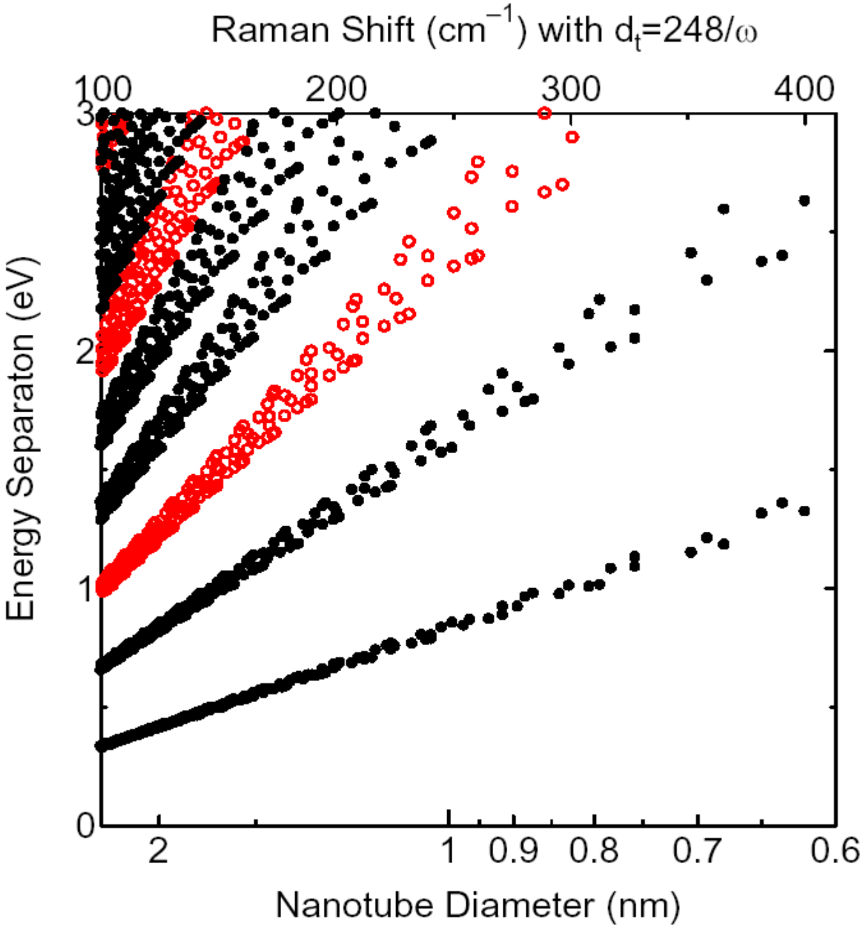
Electronic Structure of SWCNTs

1D Density of States – van Hove singularities





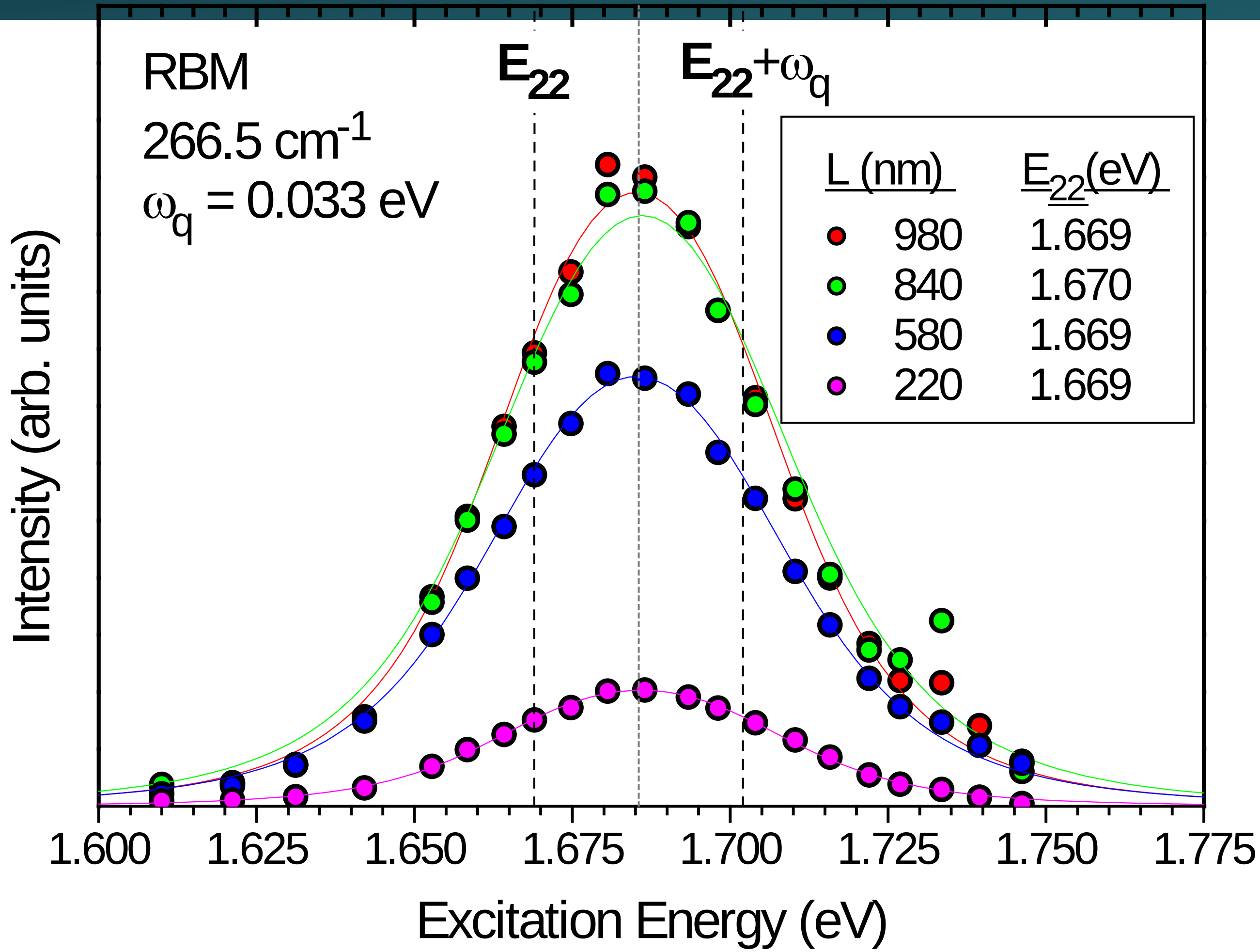
Katuara Plot



van Hove Singularities in density of states → resonance Raman.
Resonance energy with Raman peak position gives unique (n,m)

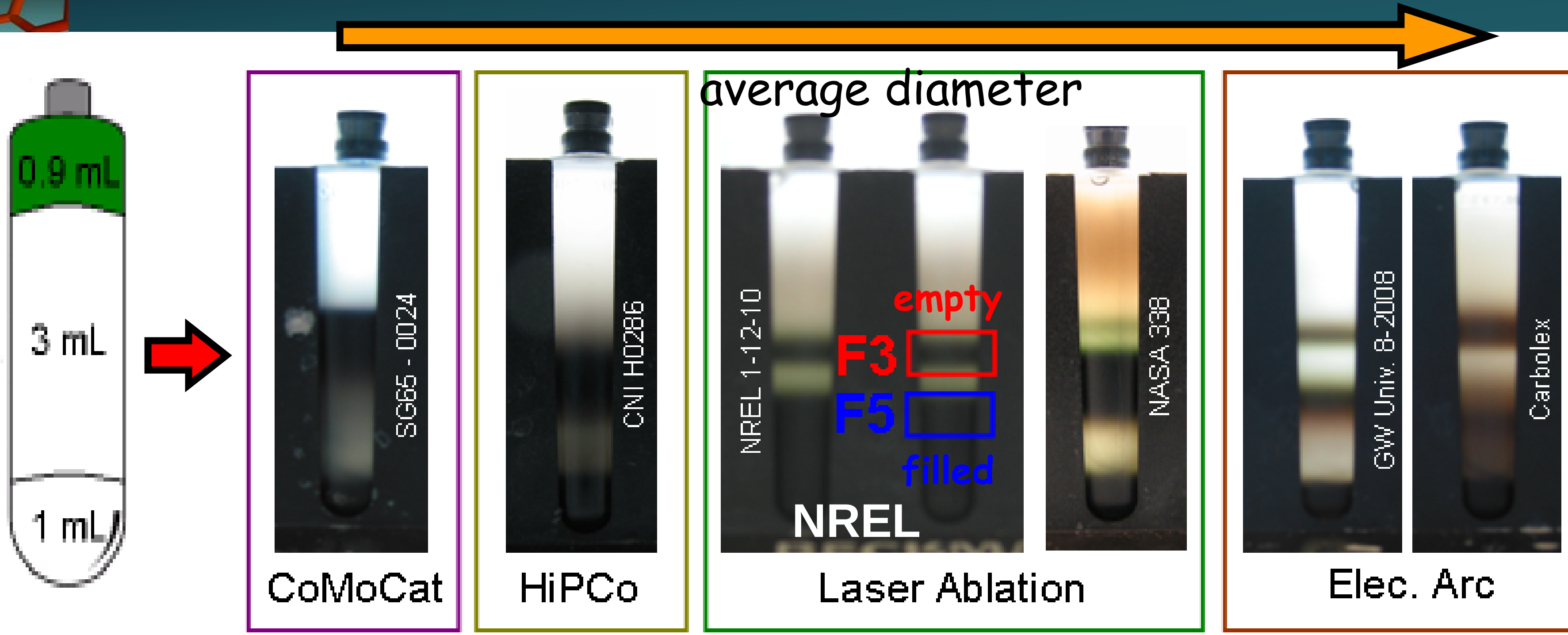
NIST

Resonance Excitation

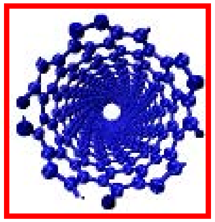


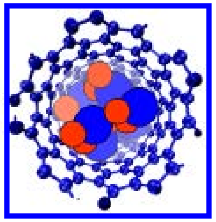
$$I_s \propto \sum_{j,k} \left| \frac{\langle 0|V_{opt}|j\rangle \langle j, N \pm 1|V_{ex-ph}|k, N\rangle \langle k|V_{opt}|0\rangle}{(E_k - E_{ii} + \mathrm{i}\,\Gamma)(E_j - E_q - E_{ii} + \mathrm{i}\,\Gamma)} \right|^2$$

Separation for various diameters / synthesis



<diam> 0.8 nm 1.0 nm 1.3 nm 1.5 nm





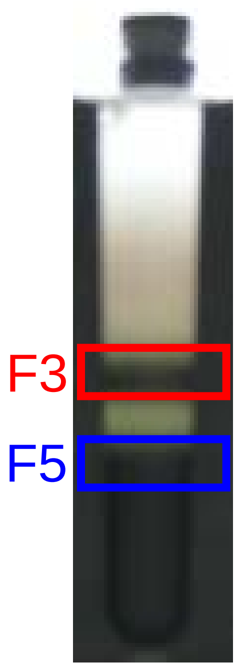
1. Separation into 2 distinct bands, increase with diameter
2. Lower band progresses further down with diameter
3. Motion of nanotube bands through medium is progressive

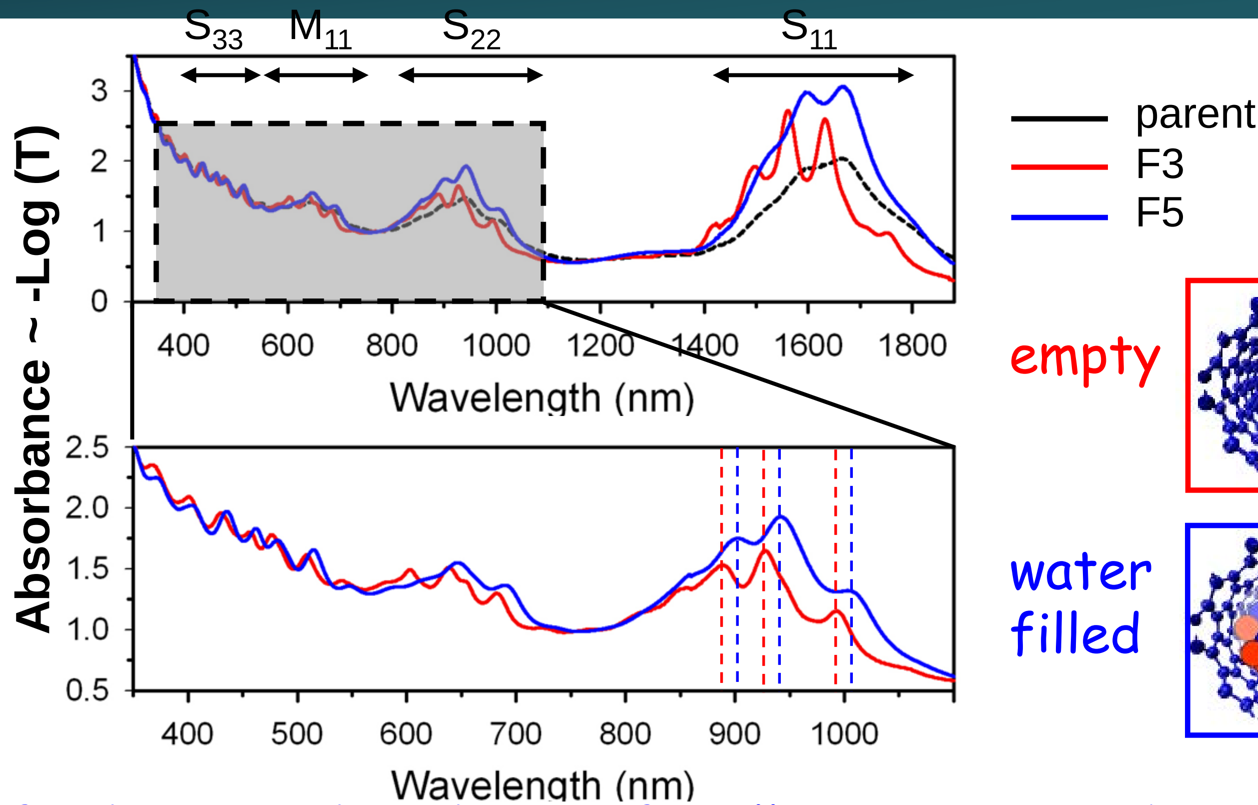
- **robust results** across various synthesis methods
- consistent with endohedral water-filling

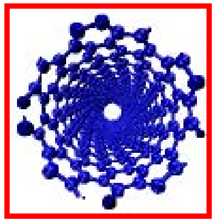
*CoMoCat excluded

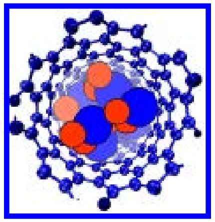
ACS Nano 5 5 3943 2011

Optical Absorption: UV-Vis-NIR





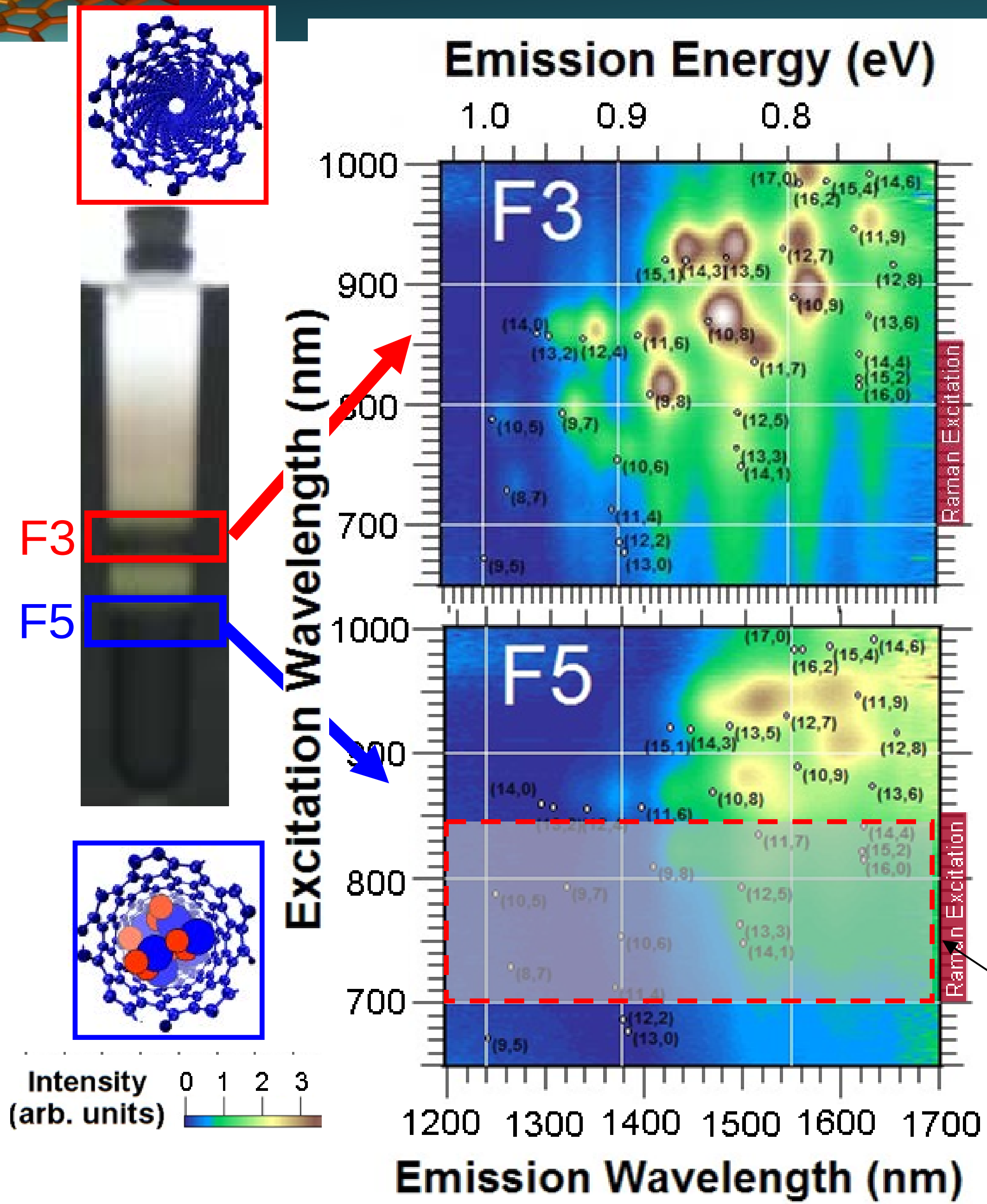




- Peaks **redshifted & broadened** in F5 for all excitonic bands, including metallic
- Similar diameter distribution in two bands
- Spectral weight of F5 comparable to or larger than F3

F5 **not** an aggregated state of F3 → filled

Near-IR Fluorescence



- Excitation & emission of F5 redshifted
- F3 brighter fluorescent intensity
- Parent materials matches F5 → typical dispersion water filled

Resonance Raman

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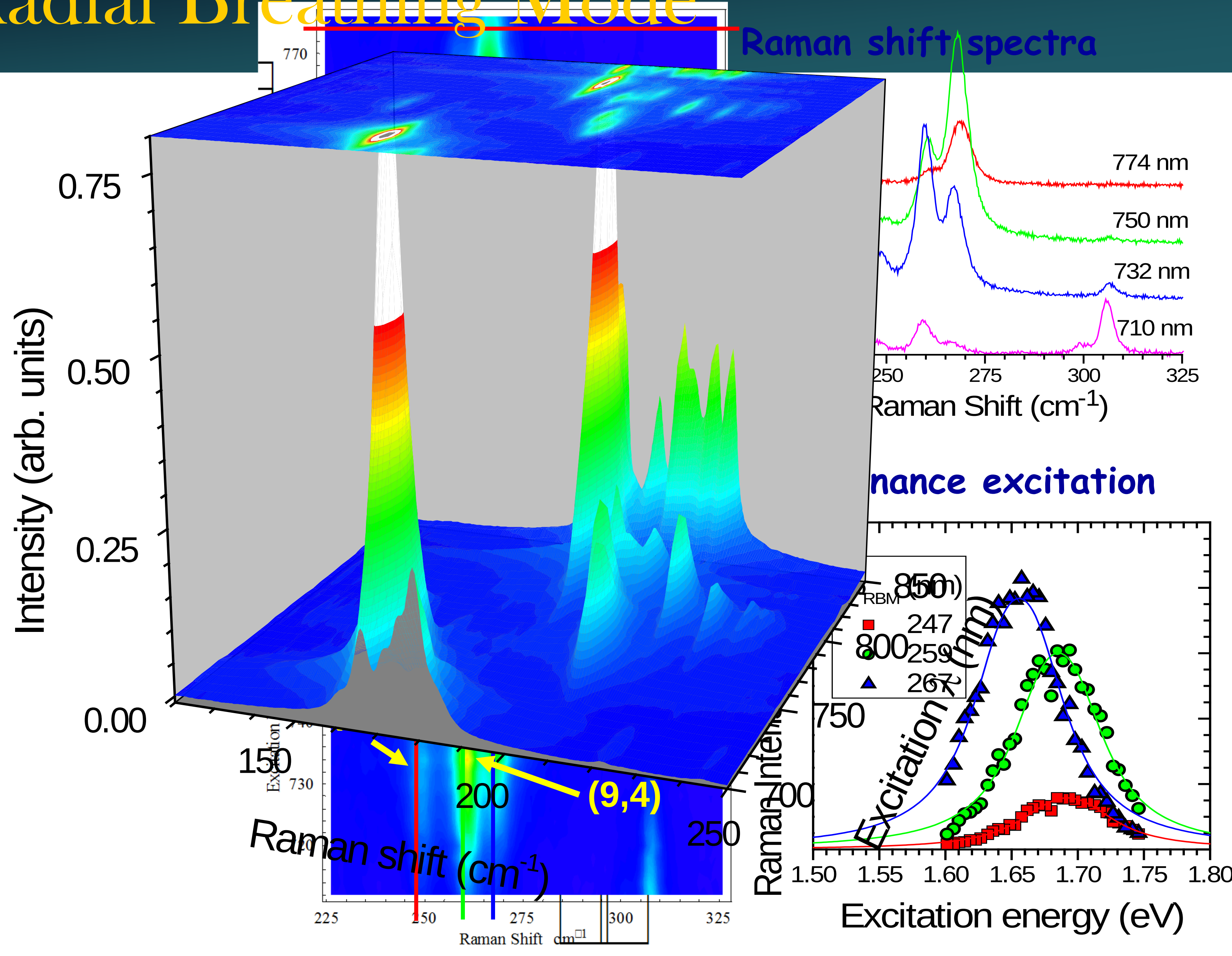
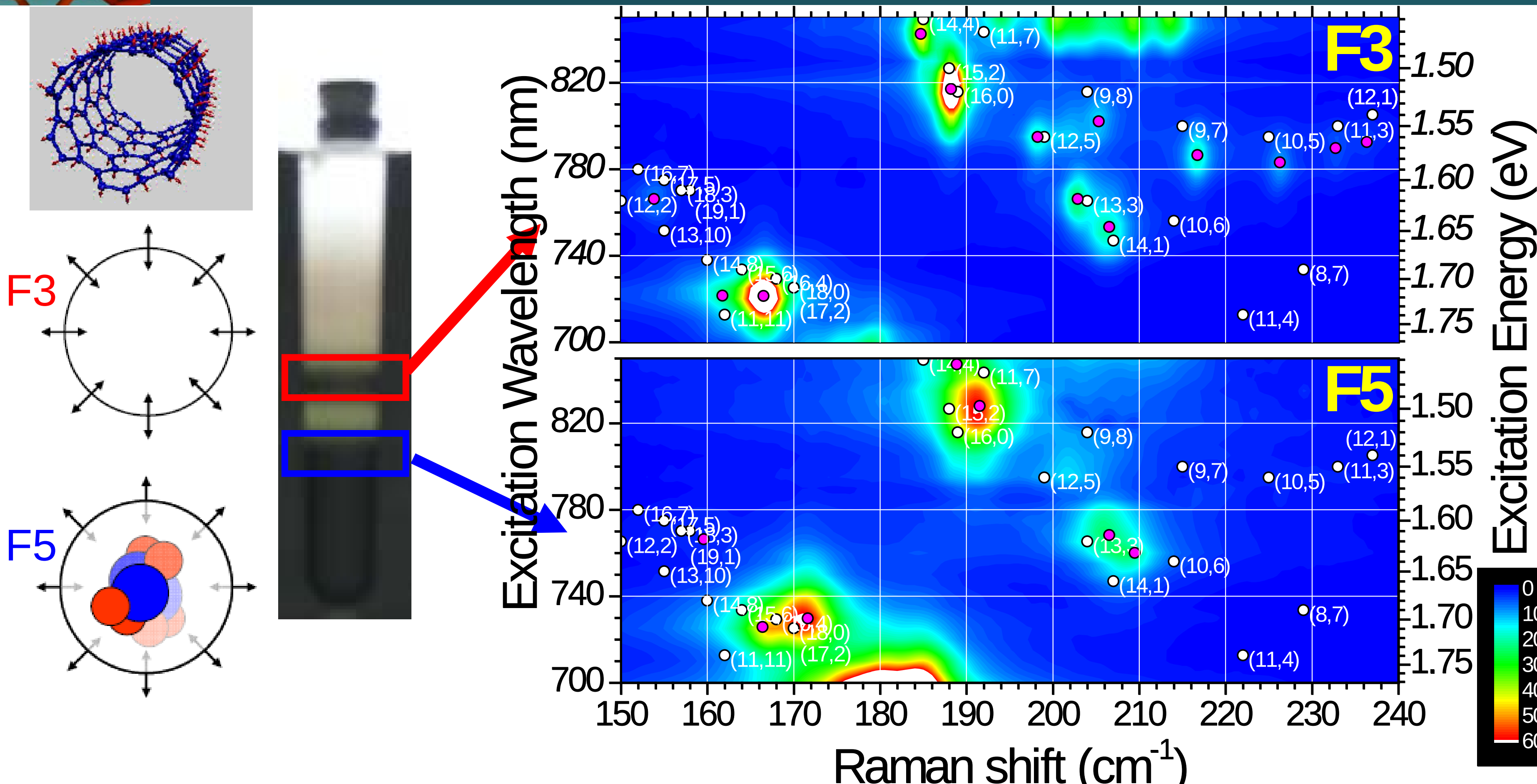
Radial Breathing Mode



Radial Breathing Modes (RBMs)



- Both semiconducting (S22) & metallic (M11) SWCNTs in resonance
- Excitation energies redshift in F5 (filled)
- RBM phonon frequencies harden (higher energy) with filling

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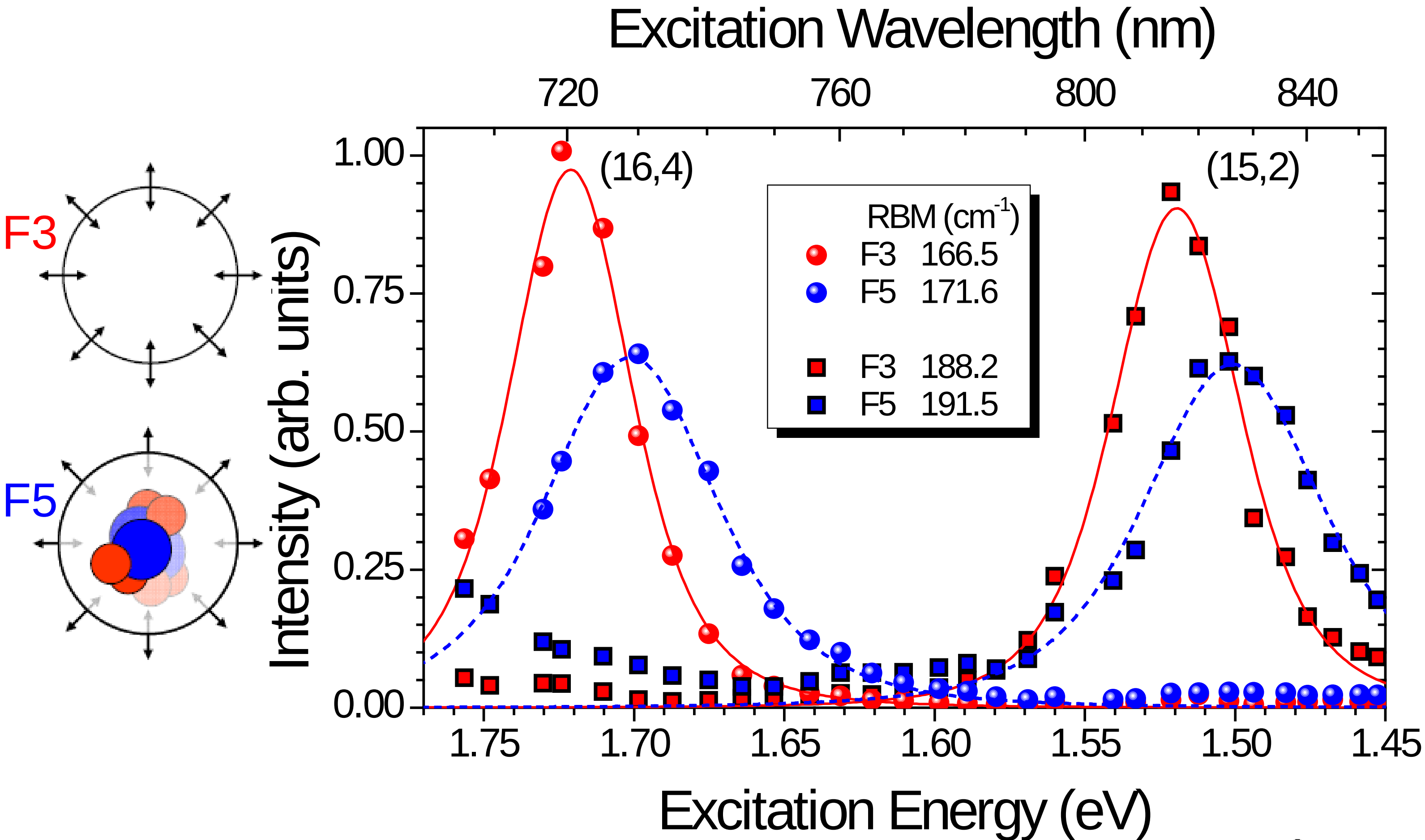
Excitation Profiles of RBMs



$$I_s \propto \sum_{j,k} \left| \frac{\langle 0|V_{opt}|j\rangle \langle j, N \pm 1|V_{ex-ph}|k, N\rangle \langle k|V_{opt}|0\rangle}{(E_k - E_{ii} + \mathrm{i}\,\Gamma)(E_j - E_q - E_{ii} + \mathrm{i}\,\Gamma)} \right|^2$$

Excitations for F5 (filled) are red-shifted and broadened

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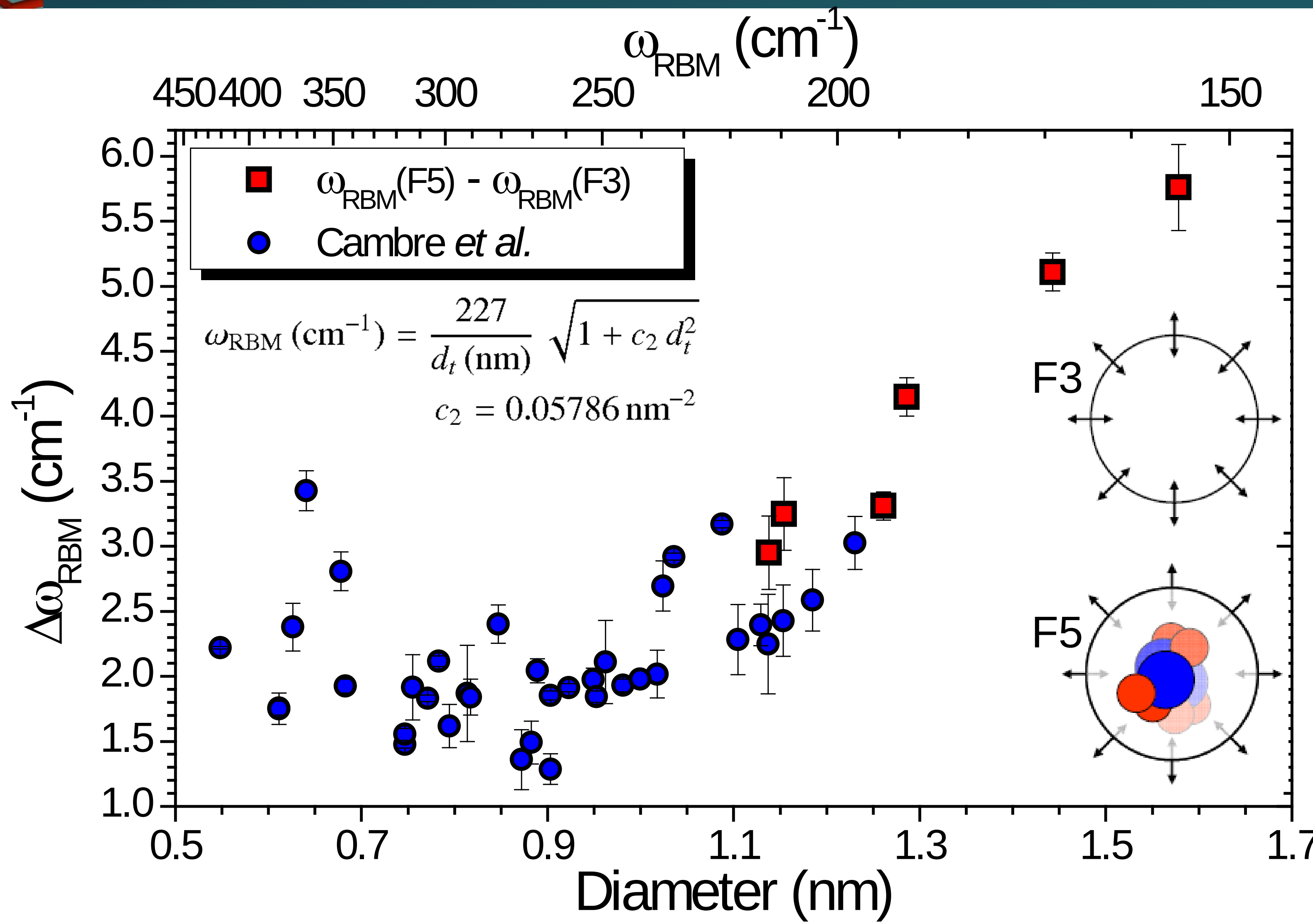
Raman RBM Shift



monotonic increase of hardening with increasing diameter

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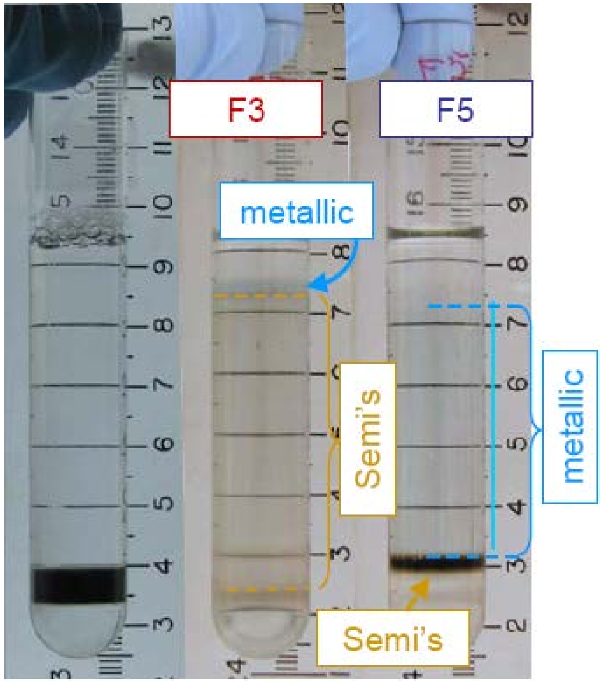
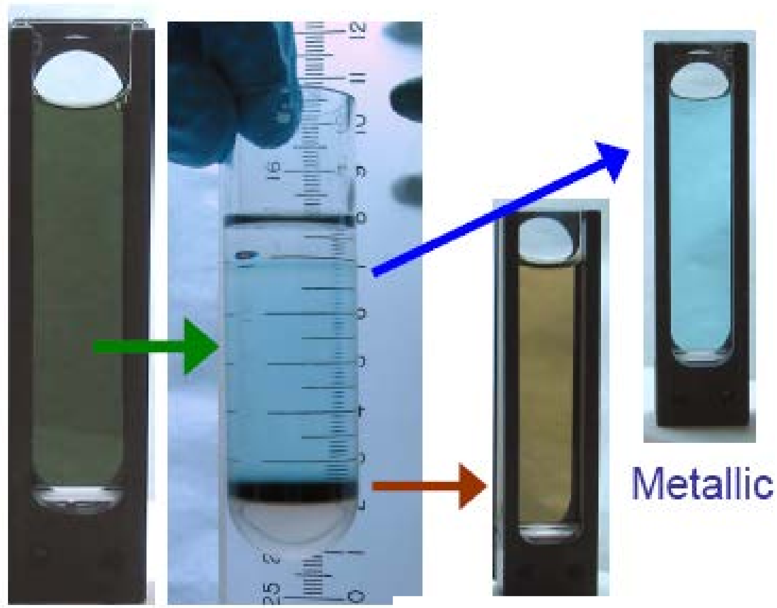
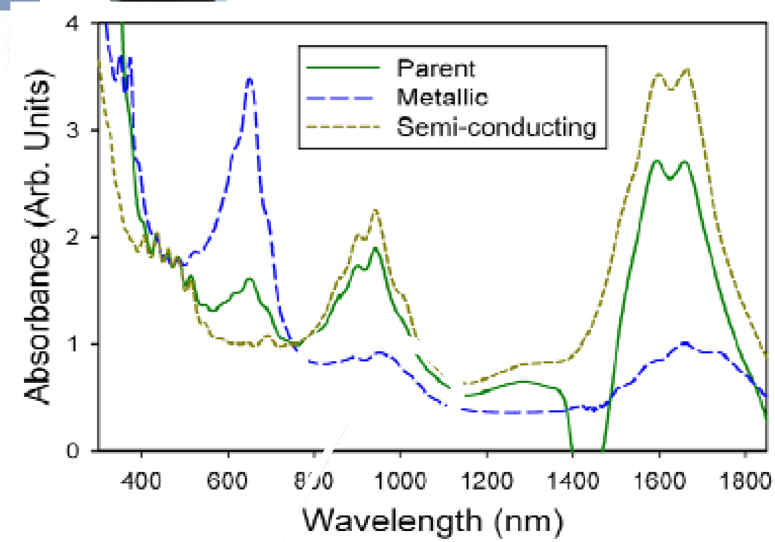
Separation by Electronic Type





- Subsequent processing and separation by electronic type
- F5 (filled) easier to separate into semi-conducting & metallic



DNA Dispersions of Carbon Nanotubes

nature | Vol 460 | 9 July 2009 | doi:10.1038/nature08116

LETTERS

DNA sequence motifs for structure-specific recognition and separation of carbon nanotubes

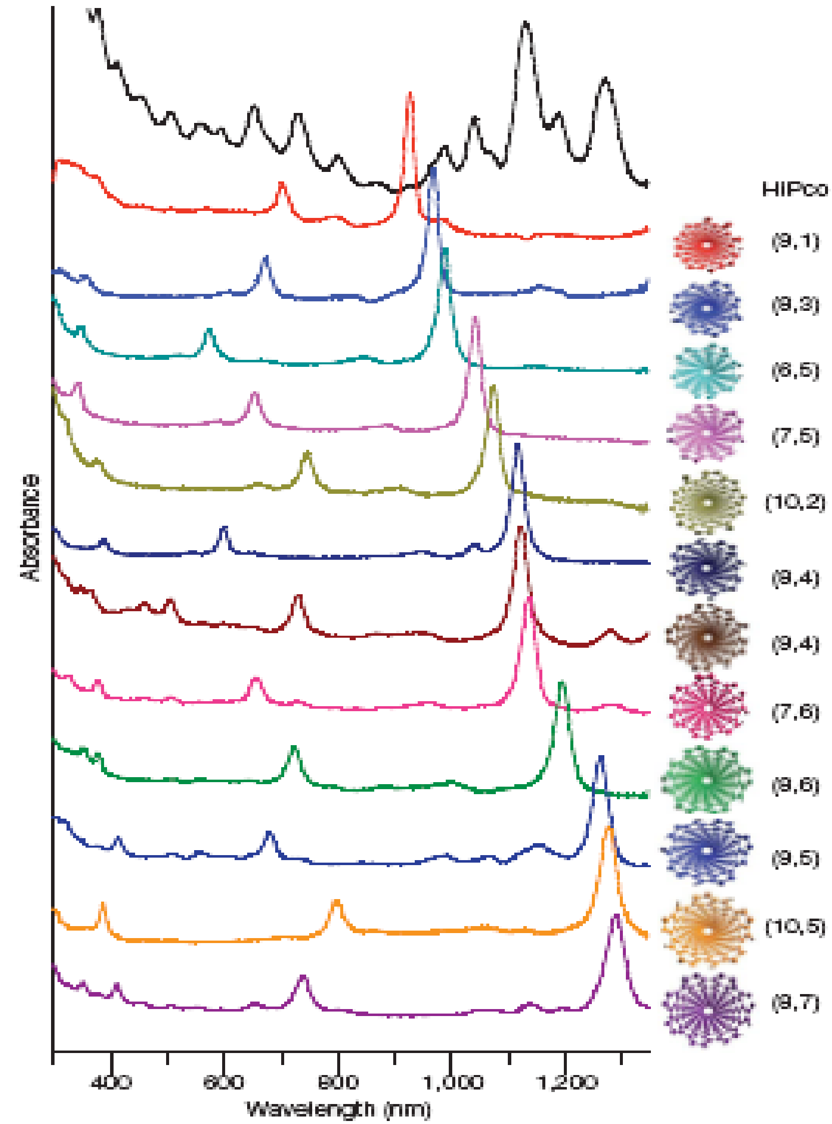
Xiaomin Tu[1], Suresh Manohar[2], Anand Jagota[2,3] & Ming Zheng[1]

Table 1 | DNA sequence versus SWNT chirality

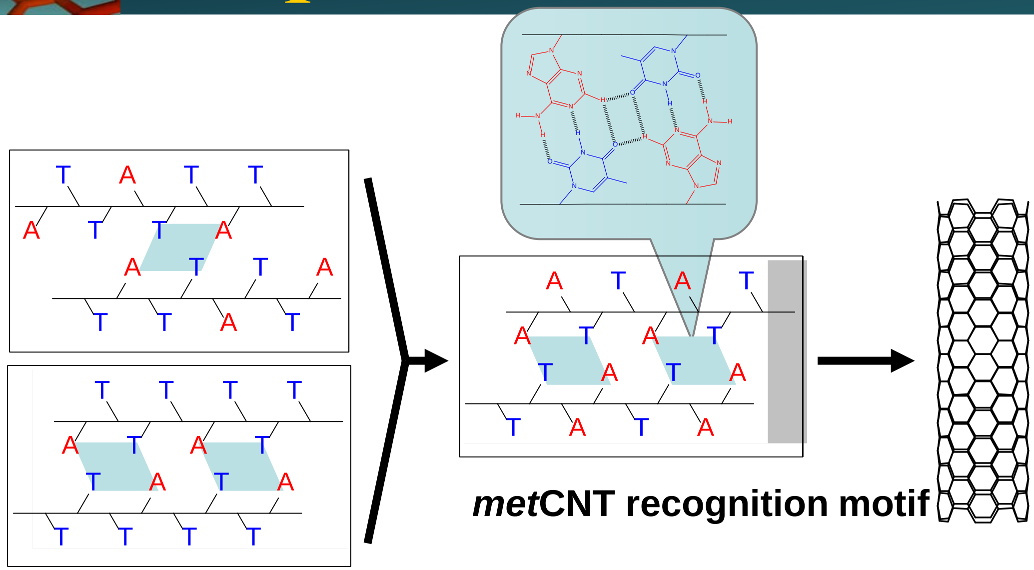
Chirality (n,m)	Sequences
(9,1)	$(TCC)_{10}$, $(TGA)_{10}$, $(CCA)_{10}$
(8,3)	$(TTA)_4TT$, $(TTA)_3TTGTT$, $(TTA)_5TT$
(6,5)	$(TAT)_4$, $(CGT)_3C$
(7,5)	$(ATT)_4$, $(ATT)_4AT$
(10,2)	$(TATT)_2TAT$
(8,4)	$(ATTT)_3$
(9,4)	$(GTC)_2GT$, $(CCG)_4$
(7,6)	$(GTT)_3G$, $(TGT)_4T$
(8,6)	$(GT)_6$, $(TATT)_3T$, $(TCG)_{10}$, $(GTC)_3$, $(TCG)_2TC$, $(TCG)_4TC$, $(GTC)_2$
(9,5)	$(TGTT)_2TGT$
(10,5)	$(TTTA)_3T$
(8,7)	$(CCG)_2CC$

DNA sequences enabling chromatographic purification of single chirality semiconducting SWNTs.

c



Sequence motif variation

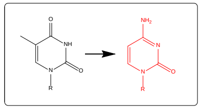


*met*CNT recognition motif

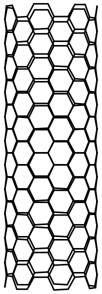
*semi*CNT recognition motifs

Enabled single chirality armchair nanotubes

TTATTATTATTATT for (8,3)



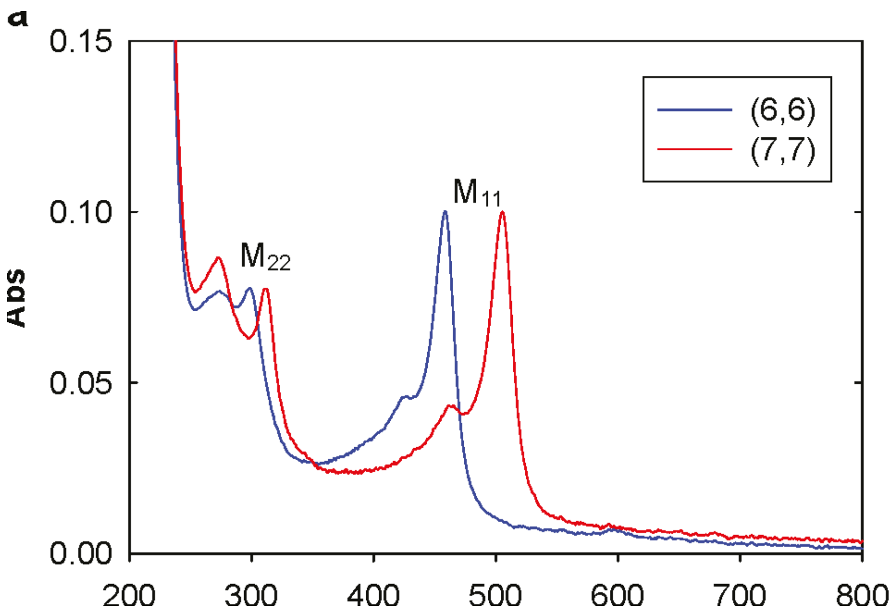
CTATTATTATTATT
T**C**ATTATTATTATT
TTA**C**TATTATTATT
TTAT**C**ATTATTATT
TTATTACTATTATT for (7,7)
TTATTAT**C**ATTATT
TTATTATTA**C**TATT
TTATTATTAT**C**ATT
TTATTATTATTA**C**T
TTATTATTATTAT**C**



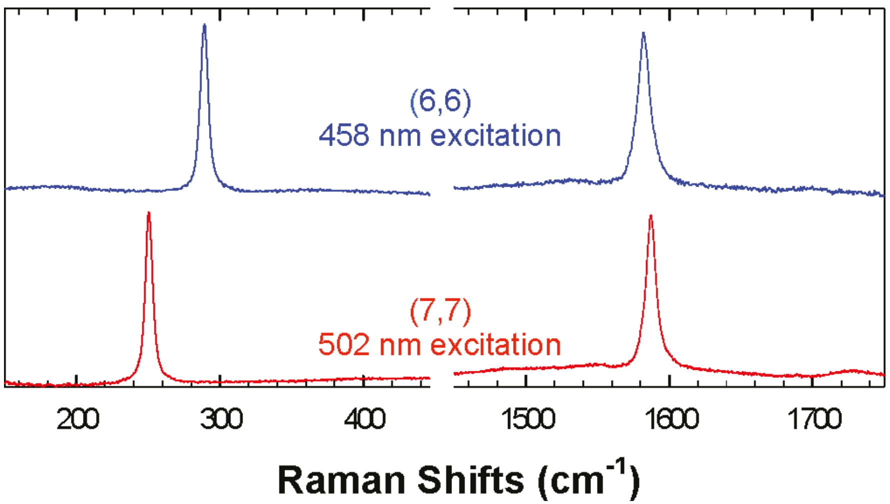
T to C scanning mutation

J. Am. Chem. Soc. 2011, 133, 129981

Optical Properties of Armchair Tubes

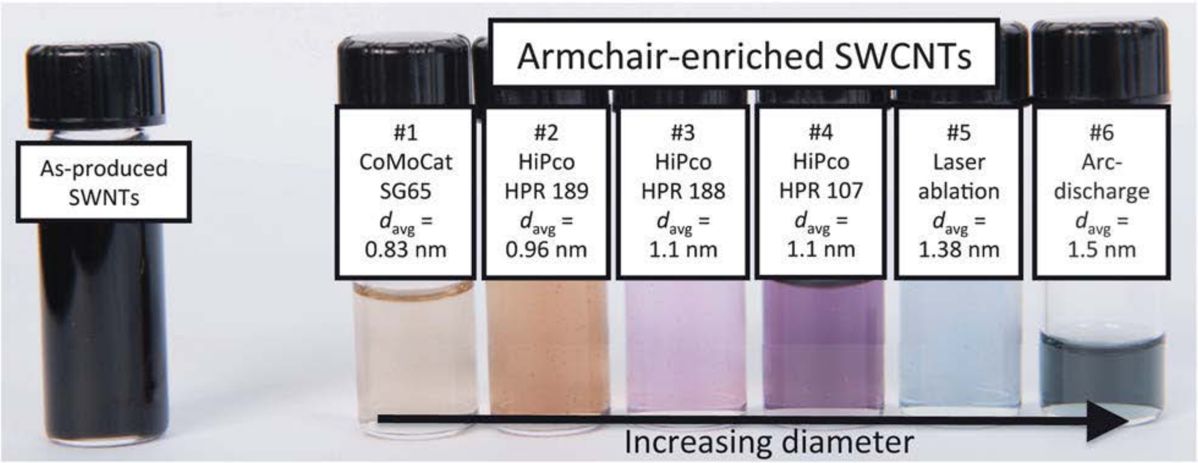


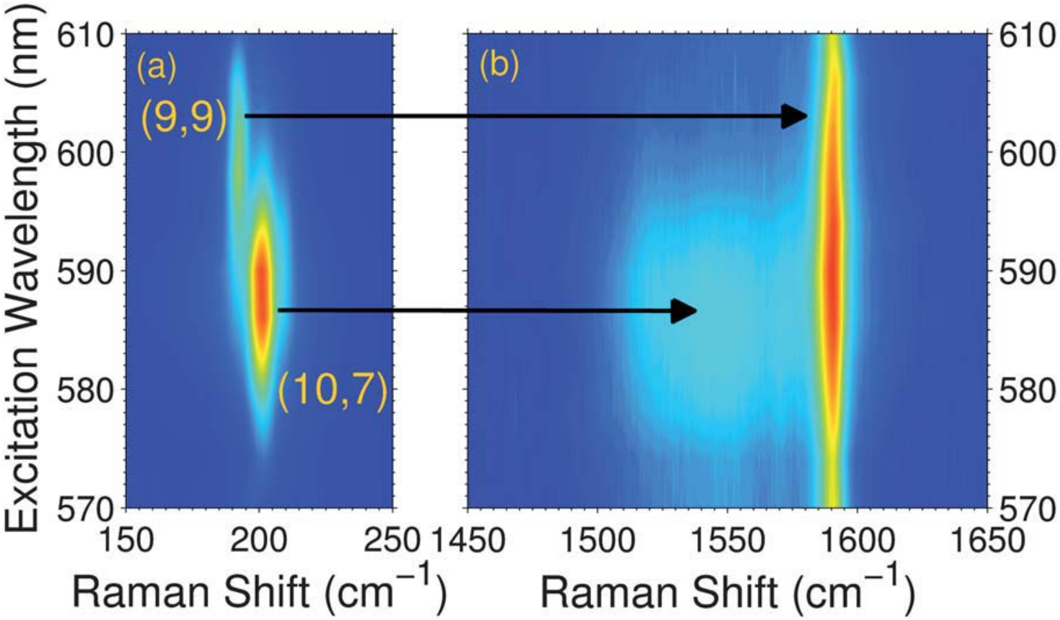
Single G band



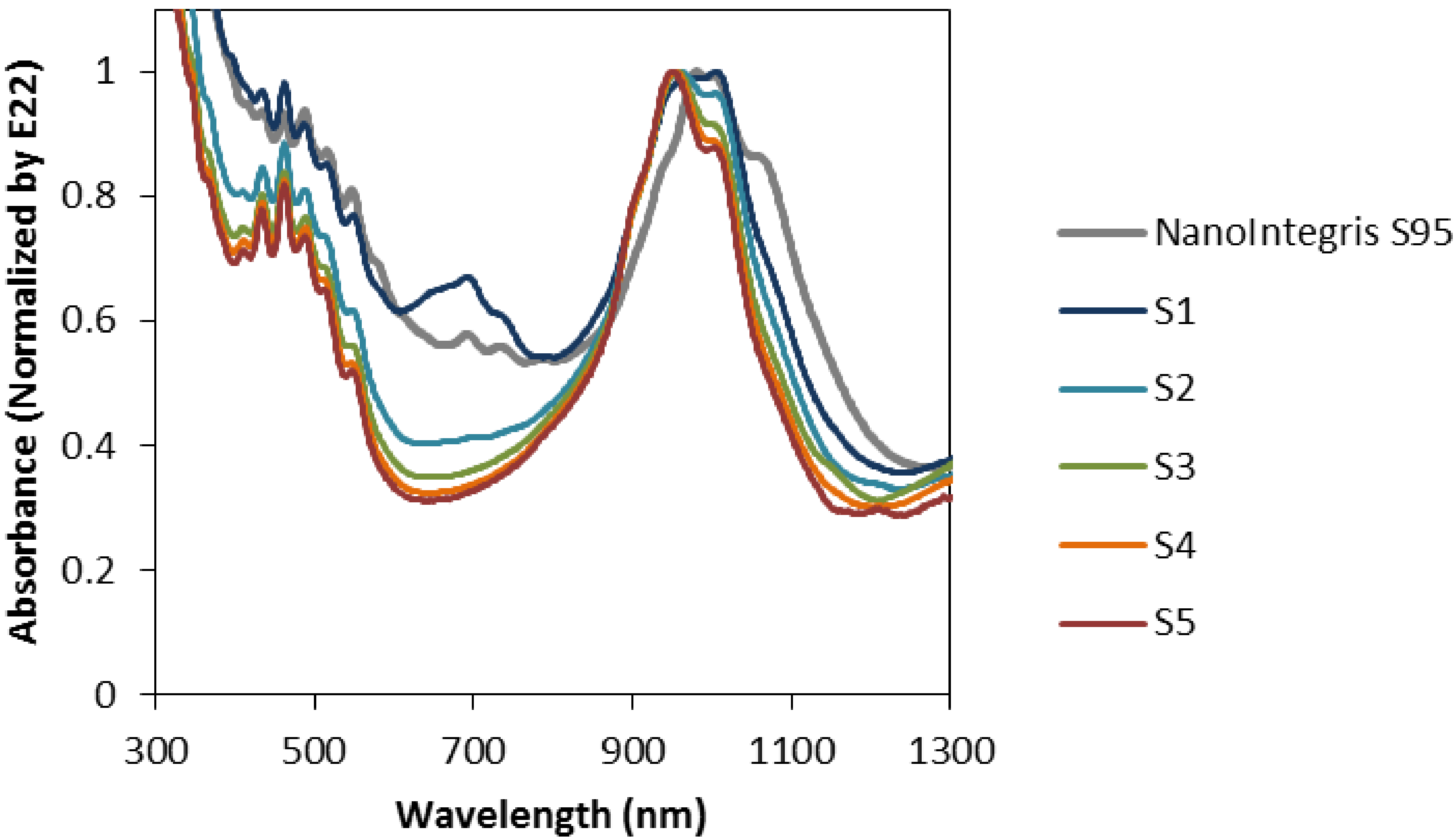
J. Am. Chem. Soc. 2011, 133, 129981

Armchair Separation by Other Techniques



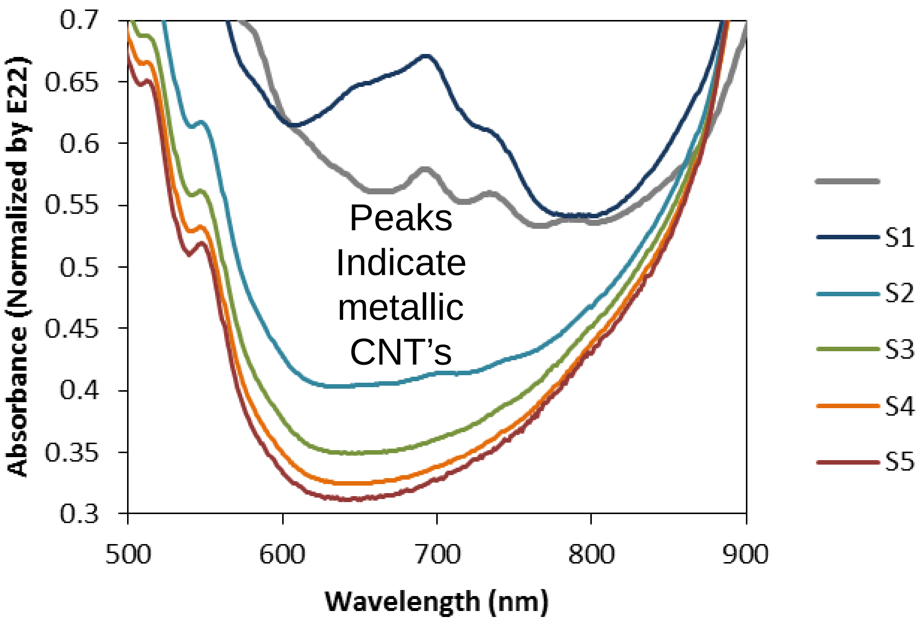


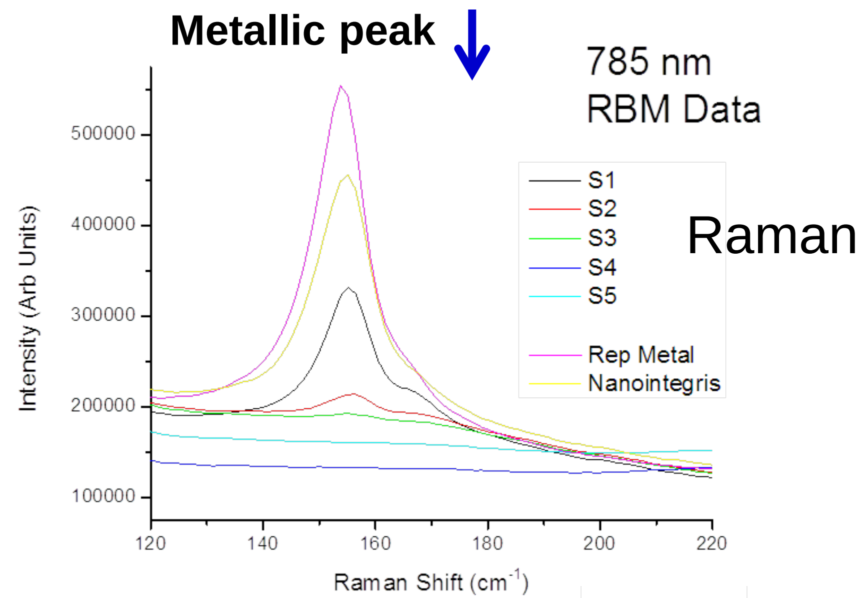
Purity metrology for SWCNTs

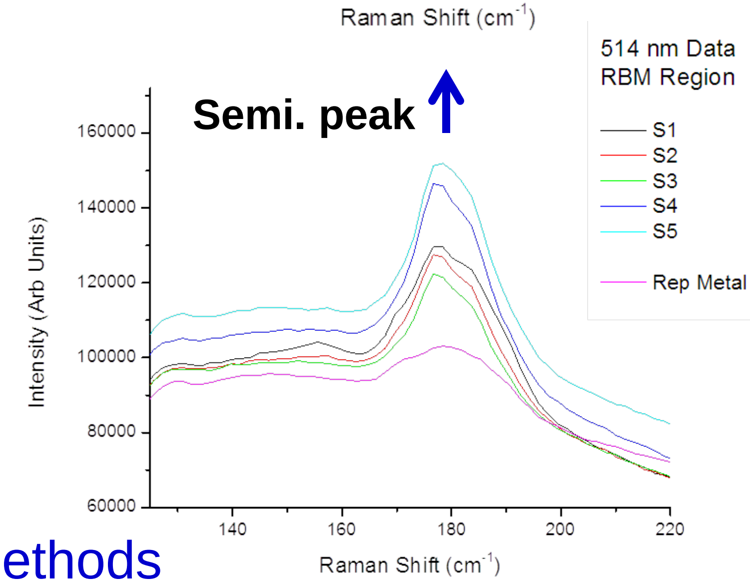


Submitted to JACS

Purity metrology for SWCNTs







SWCNT's can now be purified to levels that test the resolution of purity metrology.

- Absorbance: quick
- Raman: more powerful, higher resolution
- Goal 99.9999%

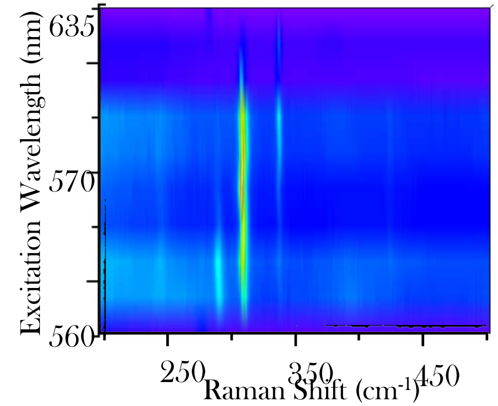
Actively improving accuracy of optical methods

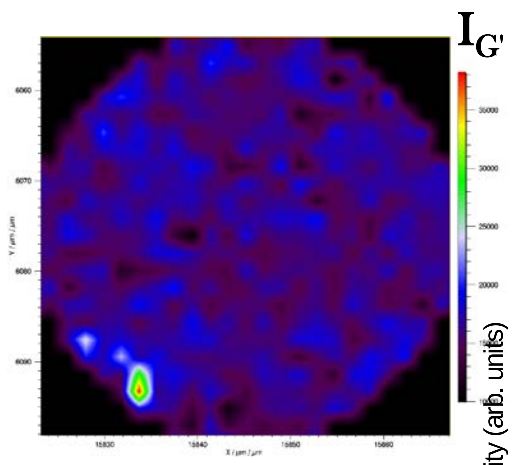
NIST

Outline

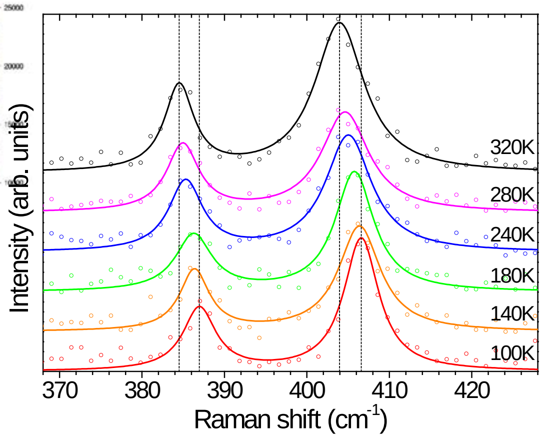
Raman spectroscopy applied to

- Carbon Nanotubes
- 2D Materials
  - Graphene
  - MoS_2

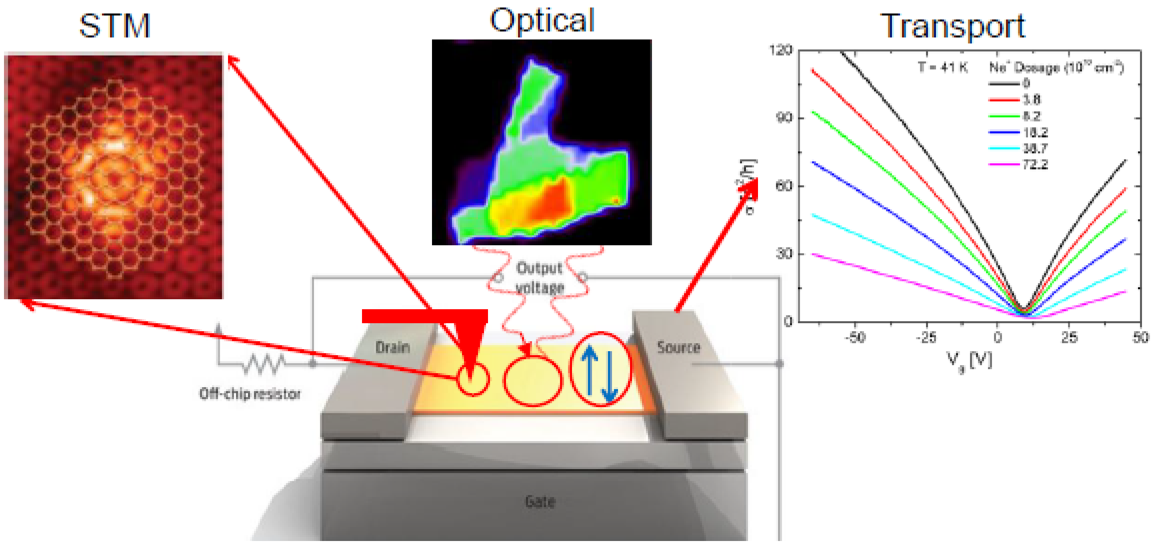




530



Bridging Measurement Length Scales to Advance Graphene Device Technologies



Twisted Graphene

NANO LETTERS — Letter
pubs.acs.org/NanoLett

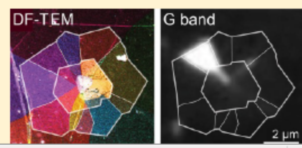
Angle-Resolved Raman Imaging of Interlayer Rotations and Interactions in Twisted Bilayer Graphene

Robin W. Havener,[†] Houlong Zhuang,[‡] Lola Brown,[§] Richard G. Hennig,[‡] and Jiwoong Park*[,§,⊥]

[†]School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, United States
[‡]Department of Materials Science and Engineering, Cornell University, Ithaca, New York 14853, United States
[§]Department of Chemistry and Chemical Biology, Cornell University, Ithaca, New York 14853, United States
[⊥]Kavli Institute at Cornell for Nanoscale Science, Cornell University, Ithaca, New York 14853, United States

Supporting Information

ABSTRACT: Few-layer graphene is a prototypical layered material, whose properties are determined by the relative orientations and interactions between layers. Exciting electrical and optical phenomena have been observed for the special case of Bernal-stacked few-layer graphene, but structure–property correlations in graphene which deviates from this structure are not well understood. Here, we combine two direct imaging techniques, dark-field transmission electron microscopy (DF-TEM) and widefield Raman imaging, to



NANO LETTERS — Letter
pubs.acs.org/NanoLett

Observation of Layer-Breathing Mode Vibrations in Few-Layer Graphene through Combination Raman Scattering

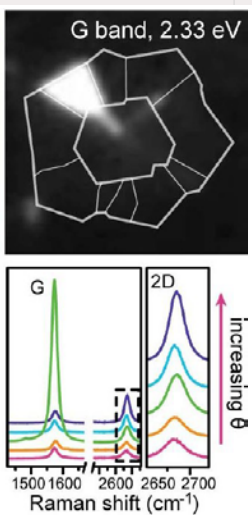
Chun Hung Lui,[†] Leandro M. Malard,[†] SukHyun Kim,[†] Gabriel Lantz,[†] François E. Laverge,[†] Riichiro Saito,[‡] and Tony F. Heinz*[,†]

[†]Departments of Physics and Electrical Engineering, Columbia University, 538 West 120th Street, New York, New York 10027, United States

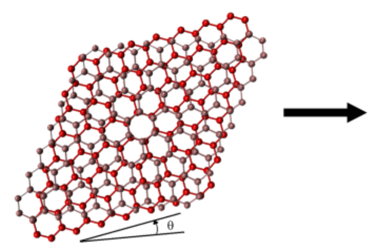
Nano Research
DOI 10.1007/s12274-013-0304-z
Research Article
ISSN 1998-0124
CN 11-5974/O4

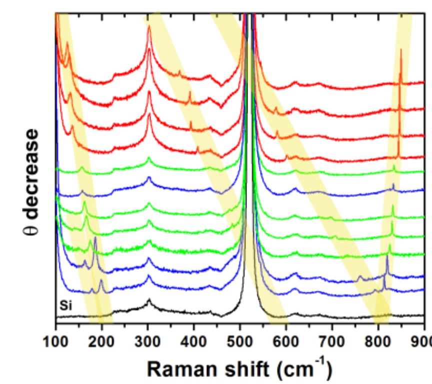
Raman-scattering study of the phonon dispersion in twisted bi-layer graphene

Jessica Campos-Delgado[1] (✉), Luiz G. Cançado[2], Carlos A. Achete[3], Ado Jorio[2], Jean-Pierre Raskin[1]



Enhanced G

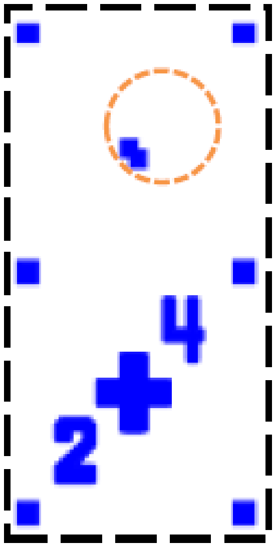




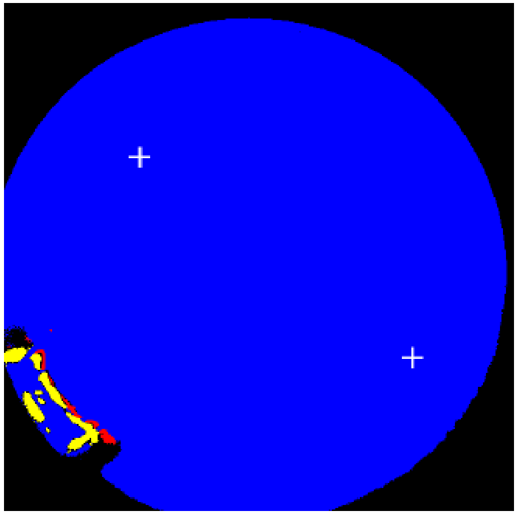
New Raman Modes

NIST

Correlating LEEM with Raman

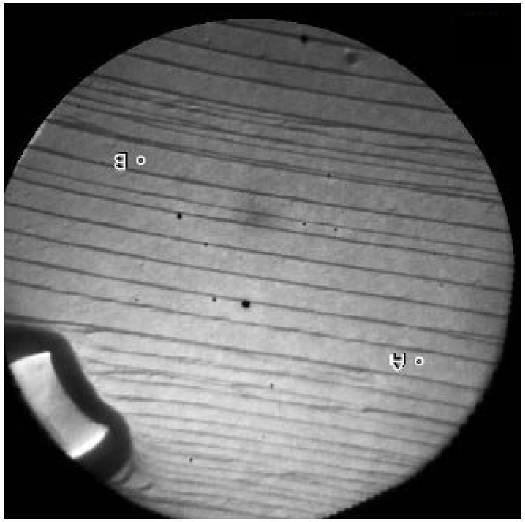


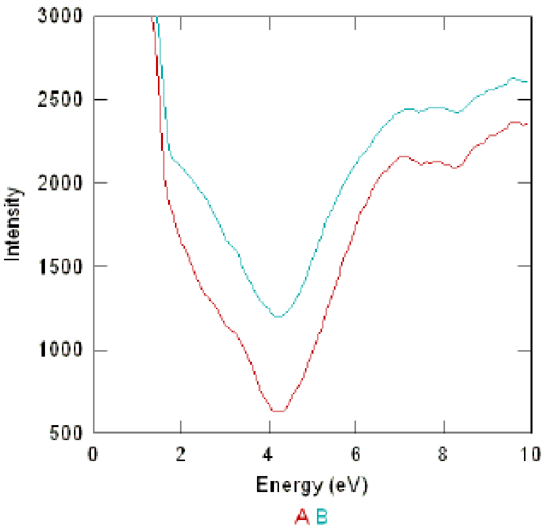
Thickness Map
Uniformly Single Layer



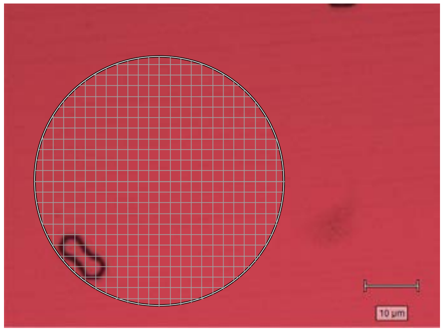
Reflectivity Image
@ 5.7 eV

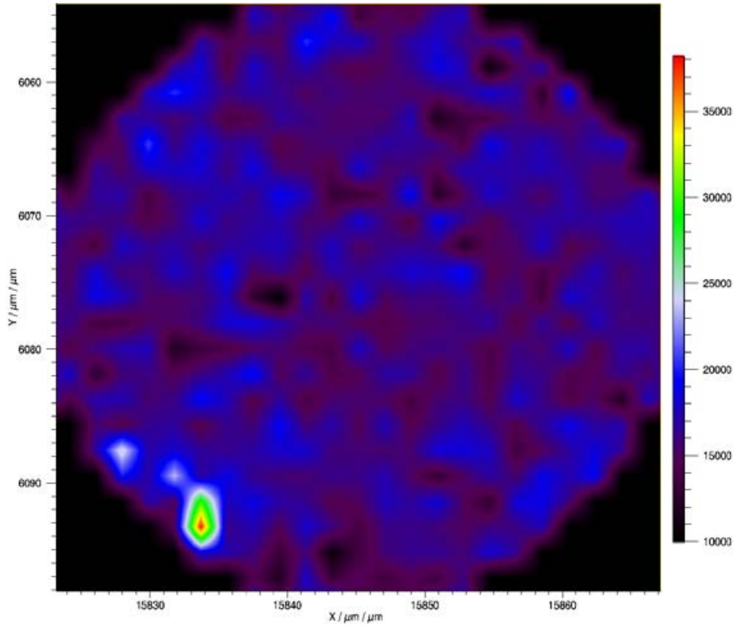
Two respective curves



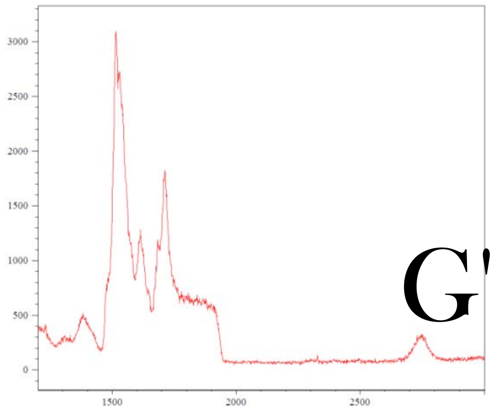


Correlating LEEM with Raman



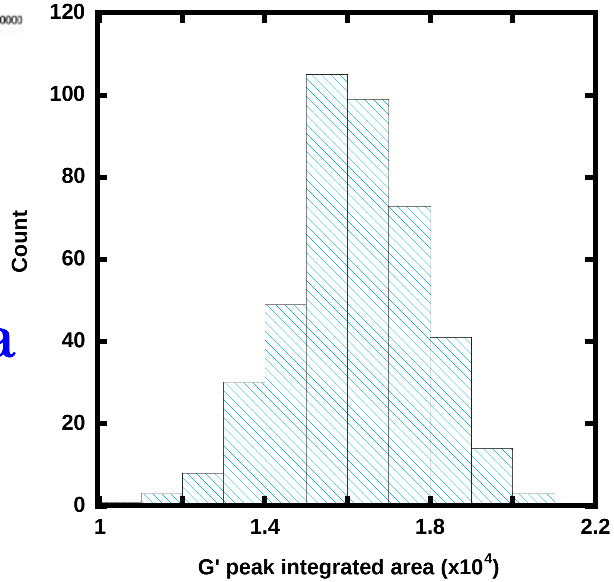


G' peak Integrated area map



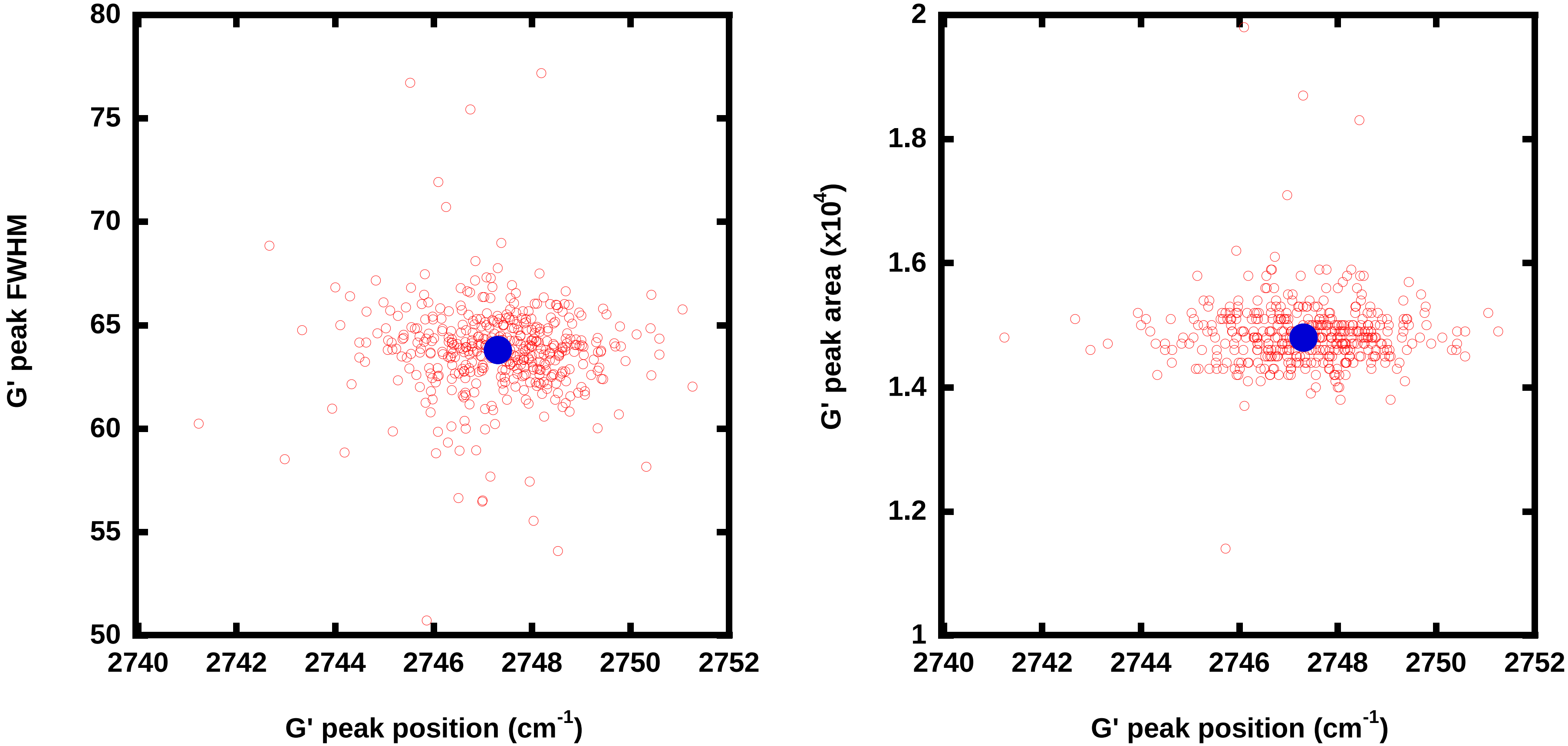
2 micron steps

Average Integrated Area 1.61 ± 0.19

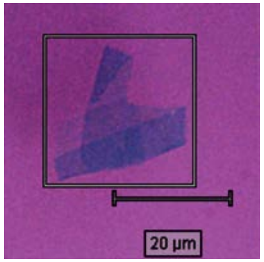


Variation in Raman Data for Single Layer

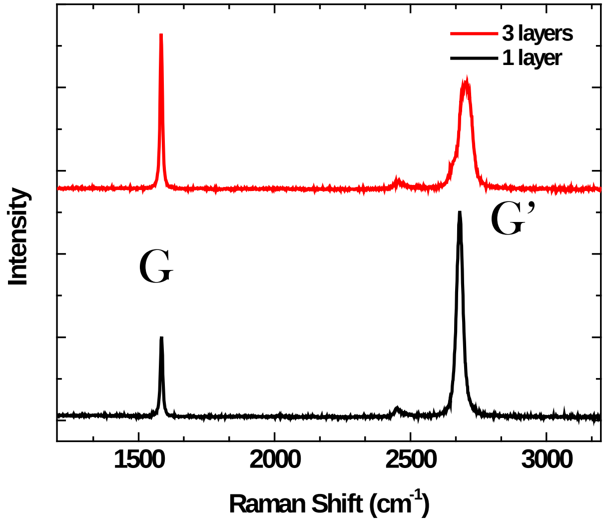
Blue dots are average value



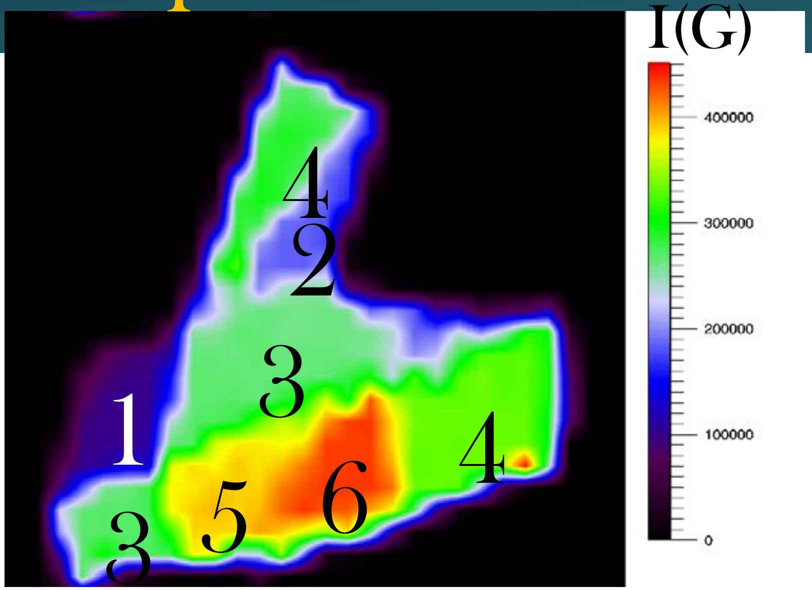
Raman Mapping on Graphene



Optical image



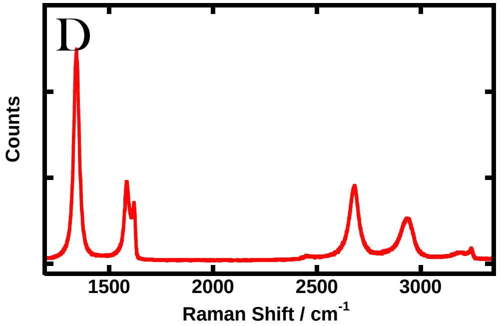
Raman Spectra

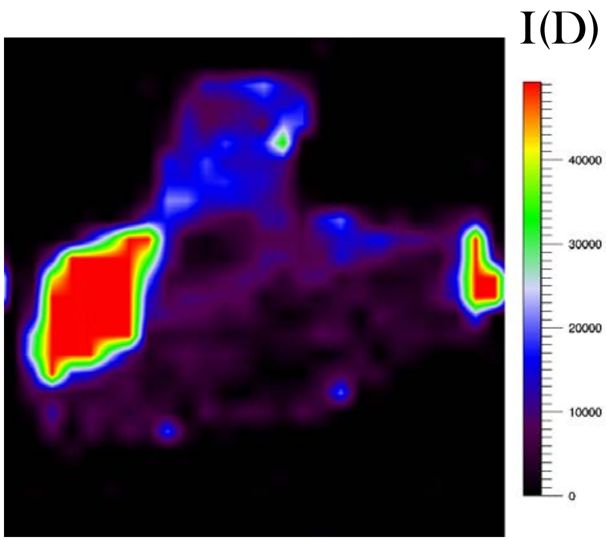


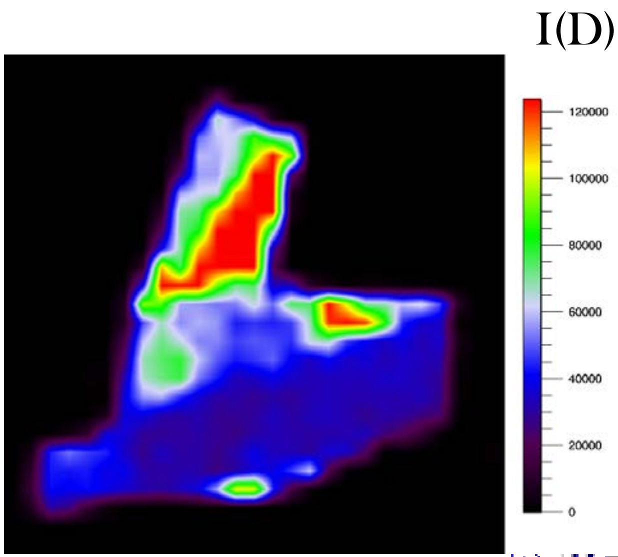
Raman mapping

Tracking chemical transformation of graphene

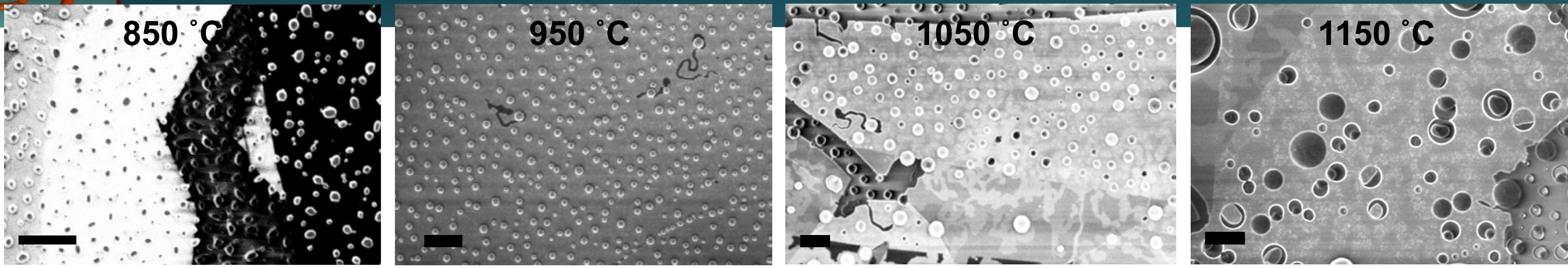
D peak shows up due to chemical reaction on graphene



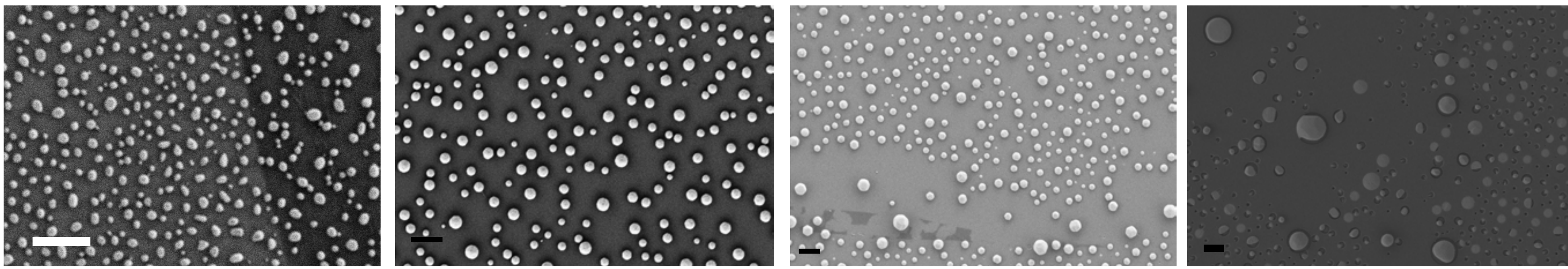




Etching Graphene by Metallic Nanoparticles



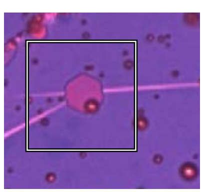
InLens detector



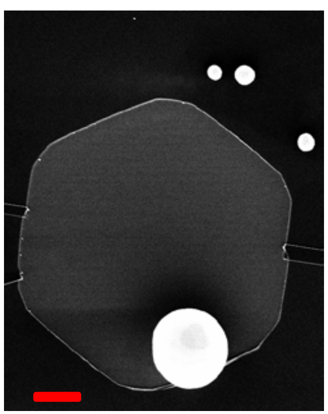
SE2 detector

scale bar: 1 μm

Hexagon
Pits
Zigzag Edge

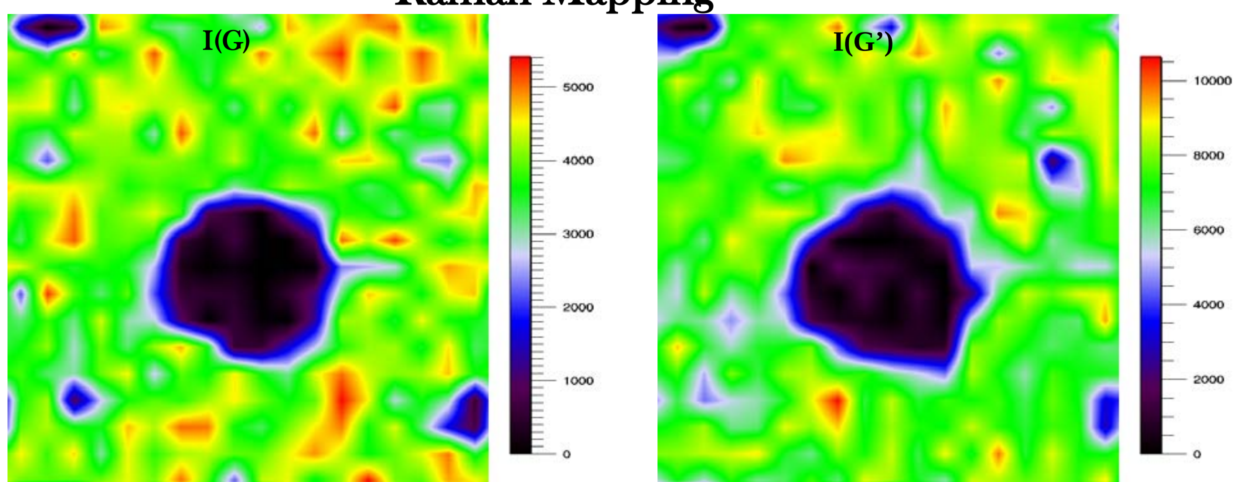


SEM



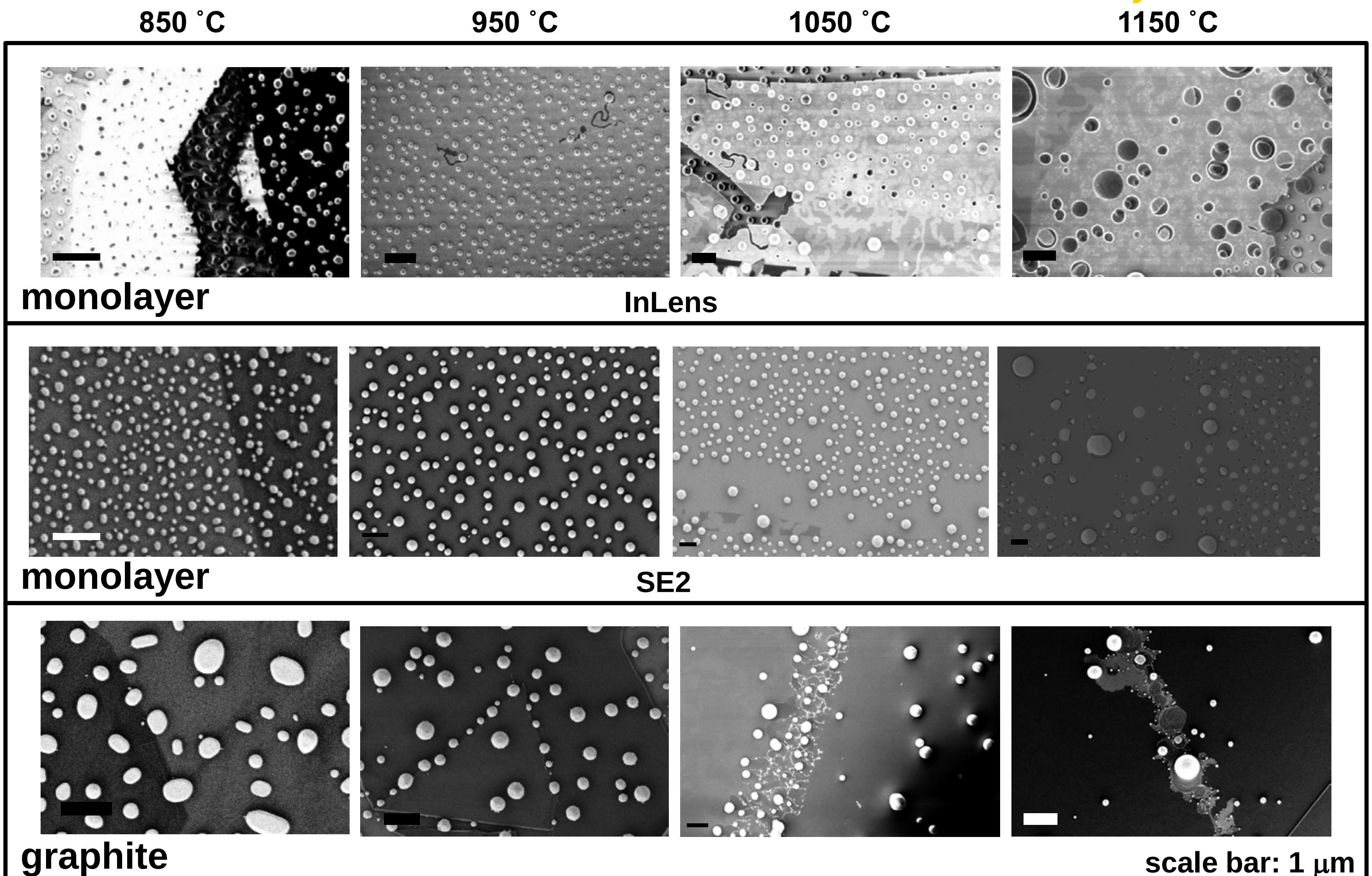
Scale bar: 1 μm

Raman Mapping



Cutting Graphene with Cu Nanoparticles

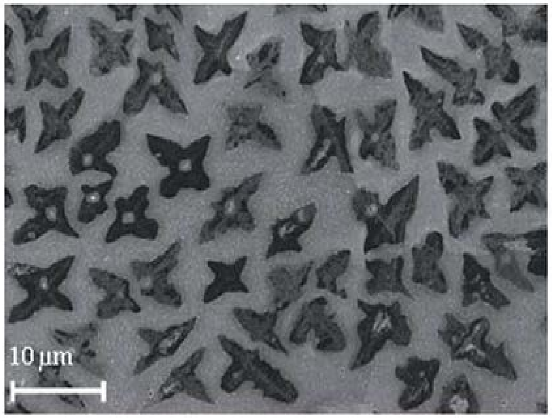
Summary of Cu Annealing

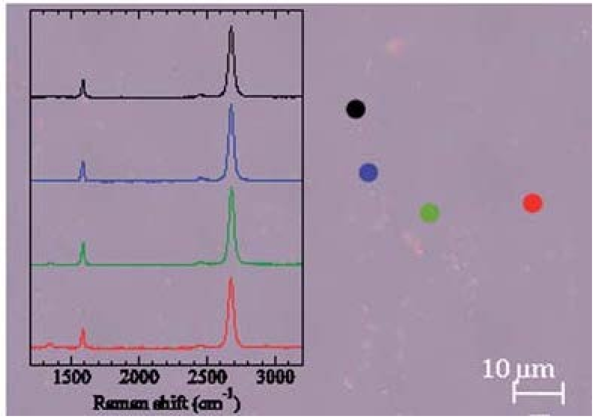


Selected as a talk for Graphene Week 2011, Austria

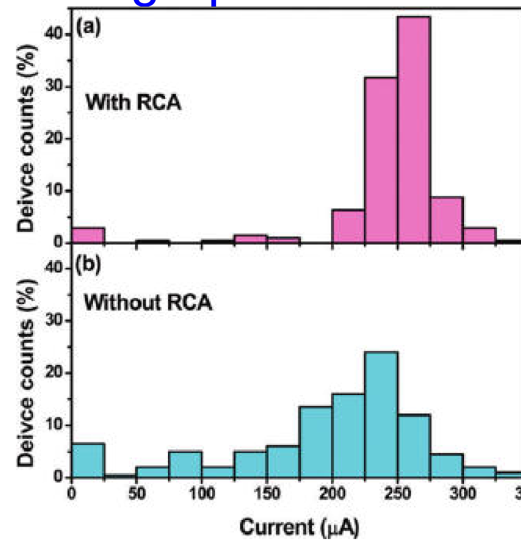
Raman Spectroscopy of Graphene

Liquid Carbon Source CVD graphene

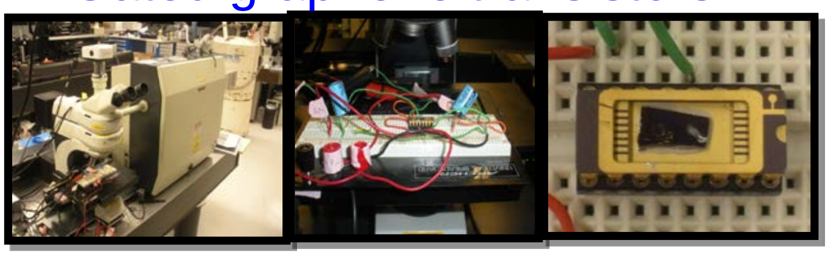


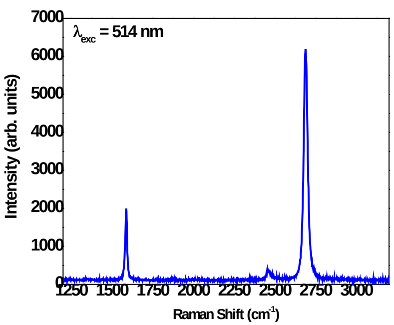


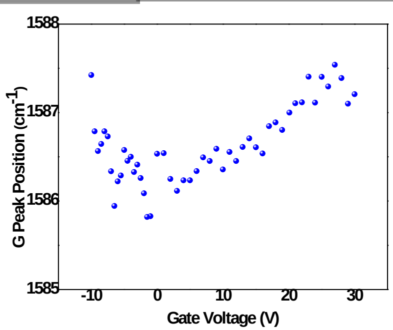
CVD graphene Transfer



Gated graphene transistors

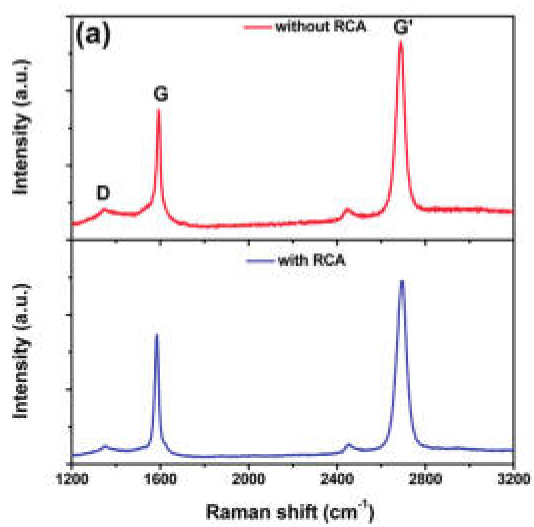


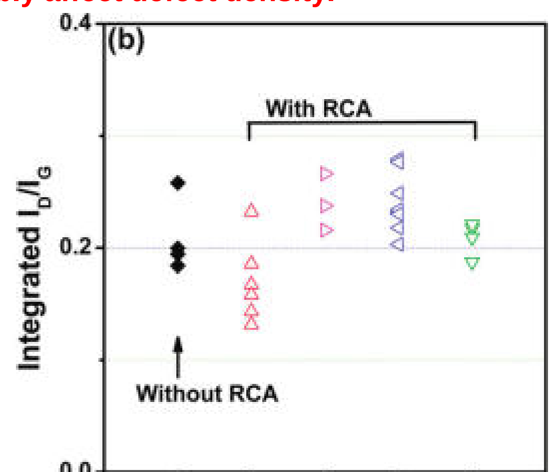




Monitors doping level in graphene devices

RCA cleaning doesn't noticeably affect defect density.





ACS NANO 5: 11 9144

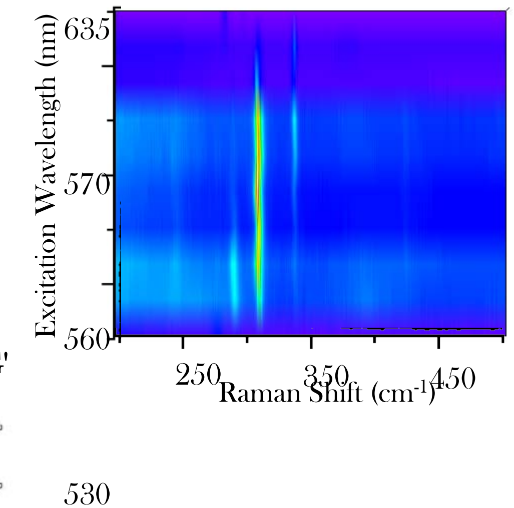
J. Mater. Chem., 2011, 21, 16057

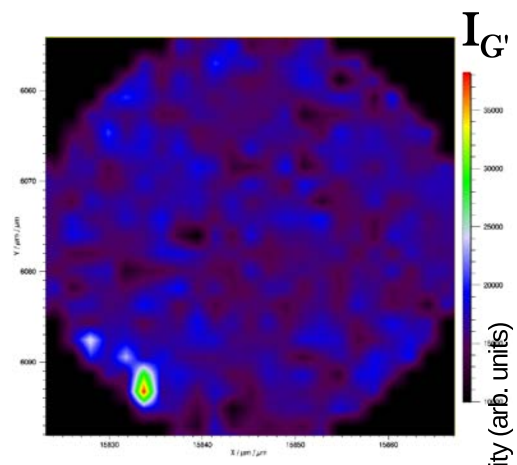
NIST

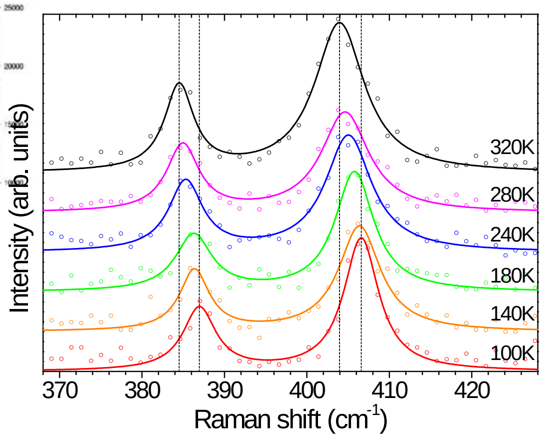
Outline

Raman spectroscopy applied to

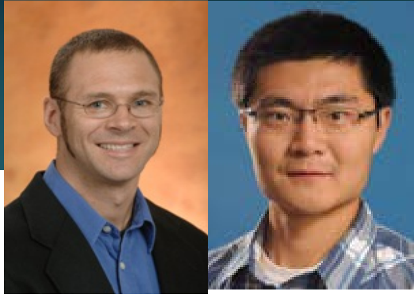
- Carbon Nanotubes
- 2D Materials
  - Graphene
  - MoS_2





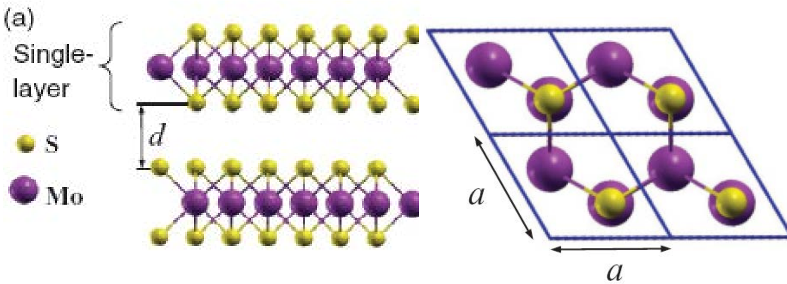


Introduction & Motivation

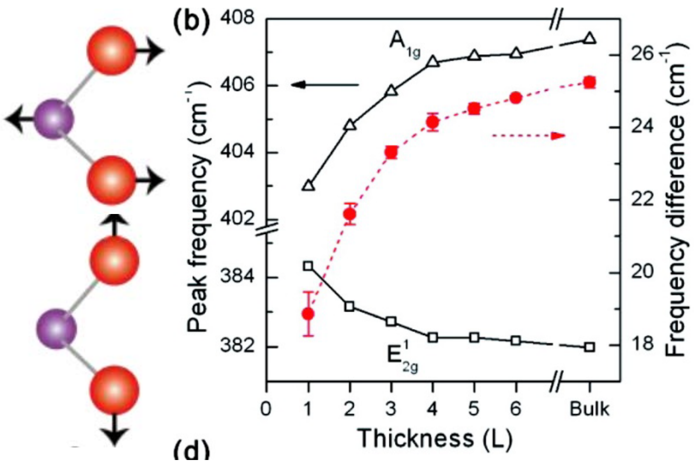


- Graphene stimulates interest in related layered materials, e.g., MoS_2:
  single layer, **direct band gap** ~1.9eV
  mobility m < graphene
  applications: transistors, photovoltaics, valleytronics
- MoS_2 structure: layered trigonal prismatic,

  1L non-centrosymmetric P6*m*2 (D_{3h})
- Raman spectroscopic characterization of MoS_2
  - two prominent Raman-active phonons symmetry
    E_{2g}^{1} (in-plane) & A_{1g} (out-of-plane)
  - quantifies layer#: peak difference
- Understanding of optical & thermal properties important for device applications



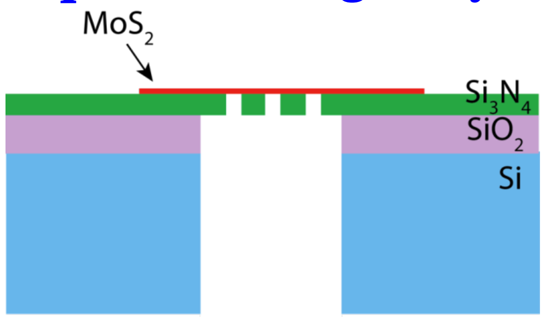
Molina-Sanchez *et al.*, PRB **84**, 155413 (2011)

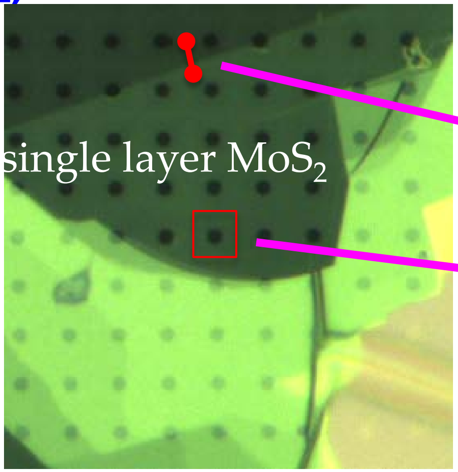


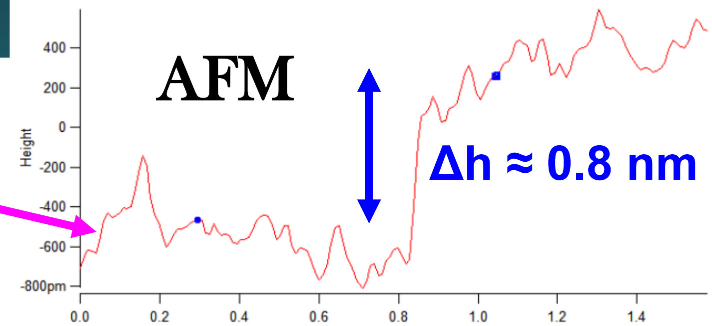
Lee *et al.*, ,ACSNano **4,** 2695 (2010)

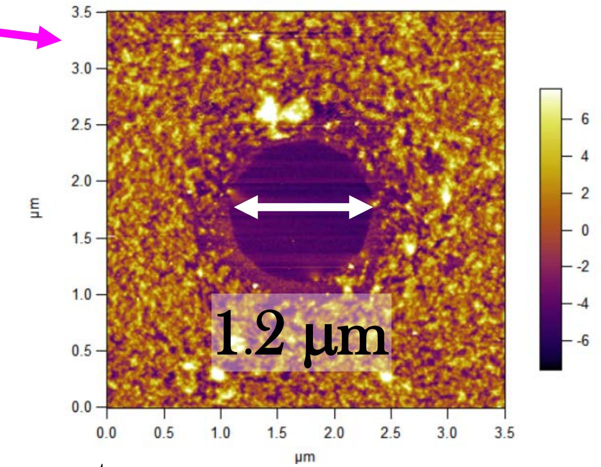
MoS_2 Monolayer Samples

Suspended single layer (1L)



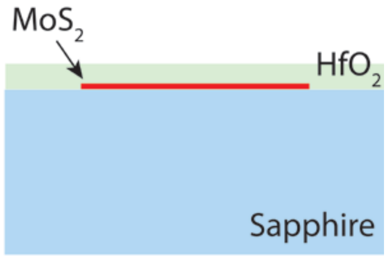


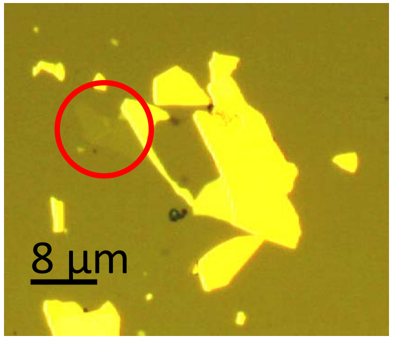




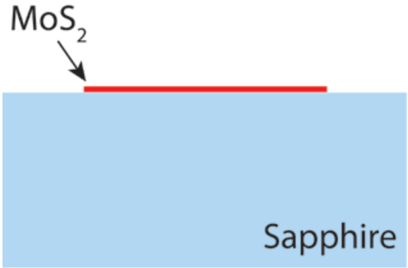
Substrate (Al_2O_3) supported

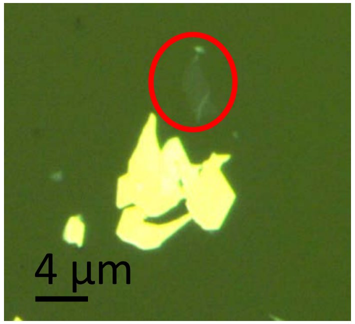
with HfO_2 overcoat





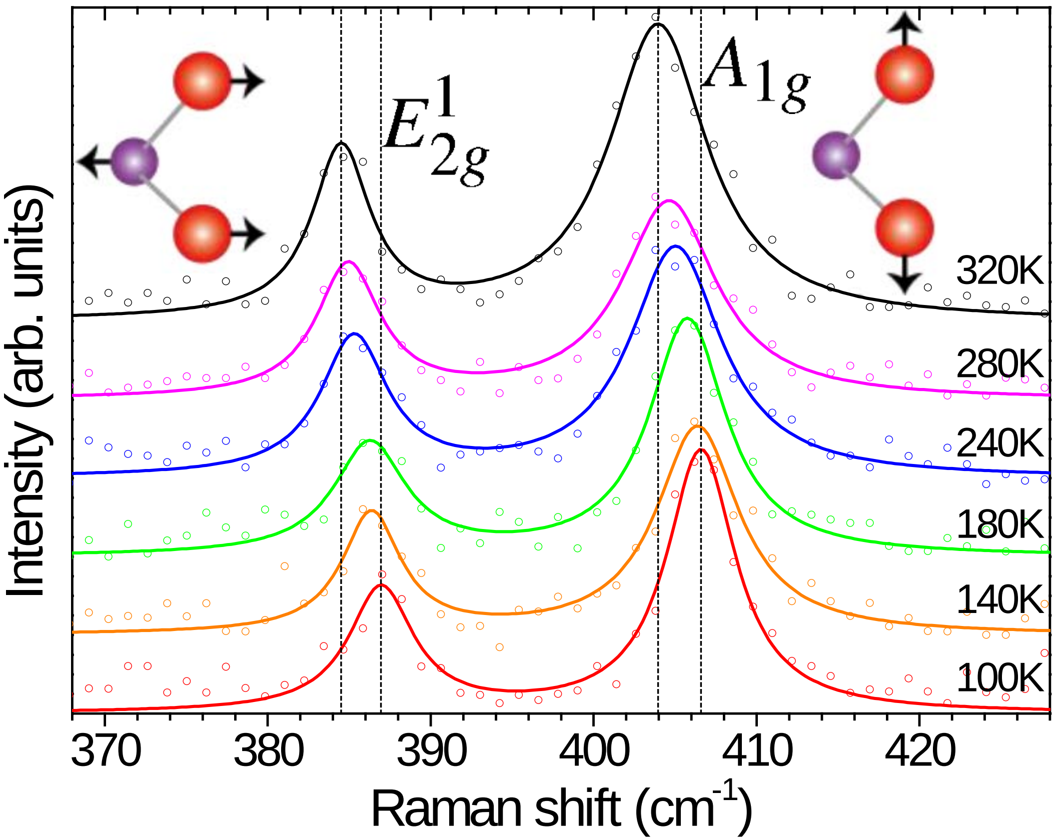
w/o HfO_2 overcoat





NIST

Temperature-Dependent Raman Spectra



λ_{ex} = 514.5 nm

< 0.2 mW (50X NA 0.55)

~ 1.2 μm diffraction-limited spot

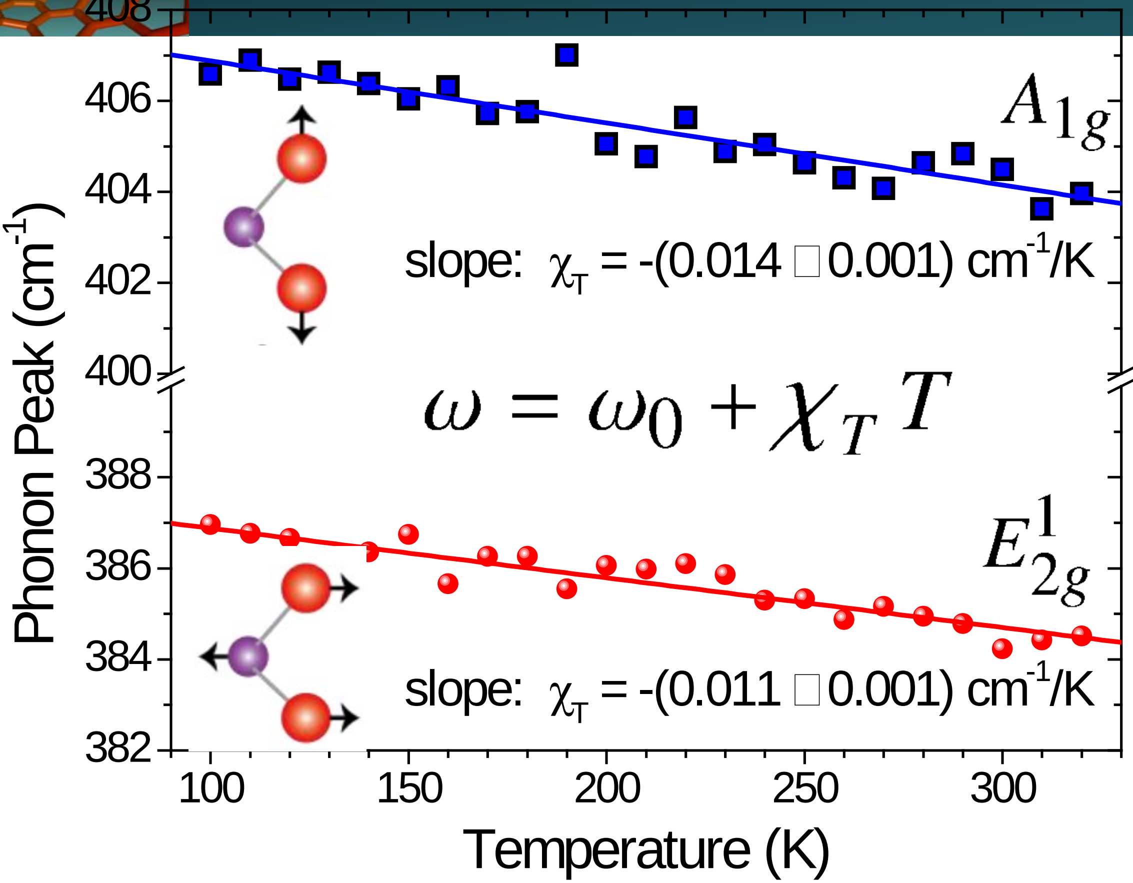
- observe two prominent Raman-active phonons:

  $E_{2g}{}^1$ (in-plane) and

  A_{1g} (out-of-plane)

- phonons **soften** with **increasing temperature**
- low optical power (intensity) to minimize thermal effects, *e.g.*, avoid local heating & sample damage

Temperature-Dependent Phonon Peaks



$$\omega = \omega_0 + \chi_T T$$

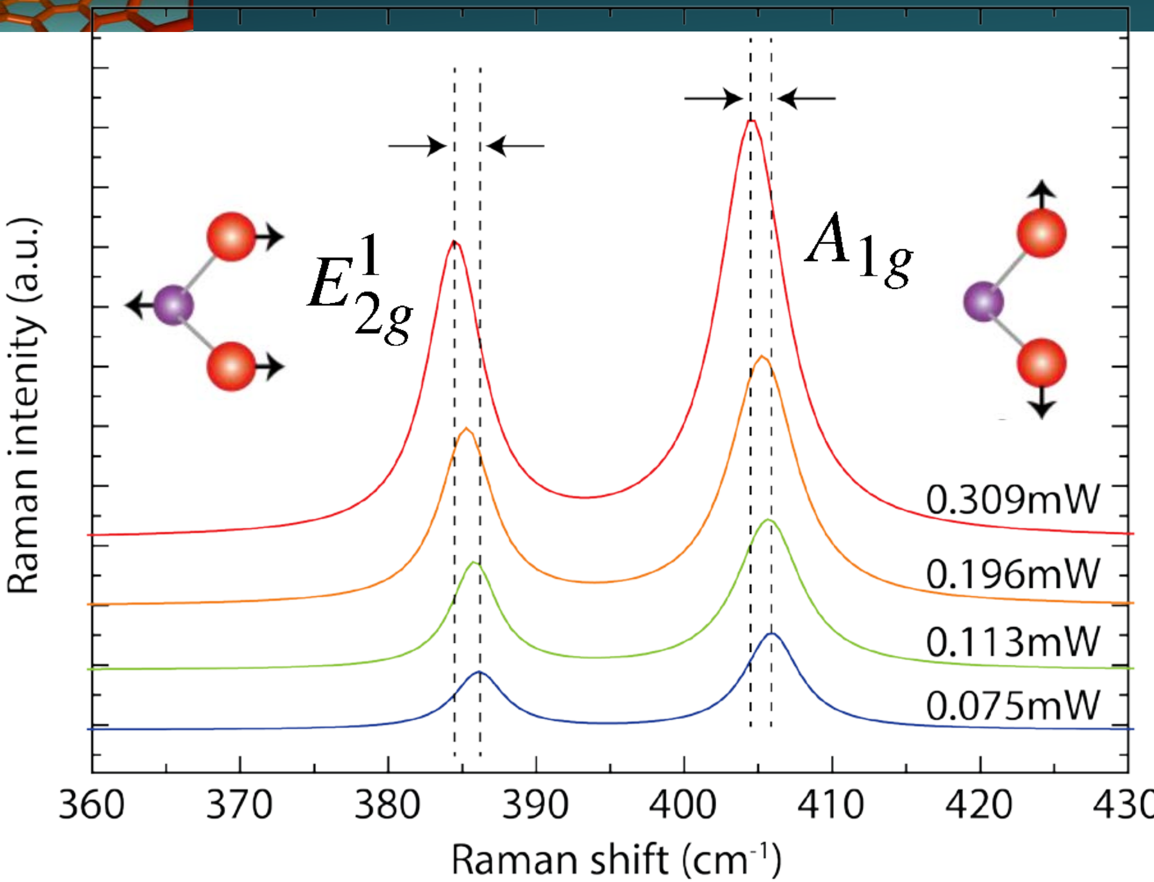
MoS_2	χ_T (cm^{-1}/mW)	
	E_{2g}^1	A_{1g}
1L suspended	**-0.011**	**-0.014**

Graphene	χ_T (cm^{-1}/mW) G-band E_{2g}
1L suspended[1]	-0.016

[1] Balandin *et al.*, NL **8**, 902 (2008)

- Phonon frequencies ***soften linearly*** with **increasing temperature**
- Anharmonic lattice potential → phonon scattering, thermal expansion
- Extract linear temperature coefficient χ_T (cm^{-1}/K)
- A_{1g} slightly more sensitive to temperature change

Laser Power-Dependent Raman Spectra



room temperature

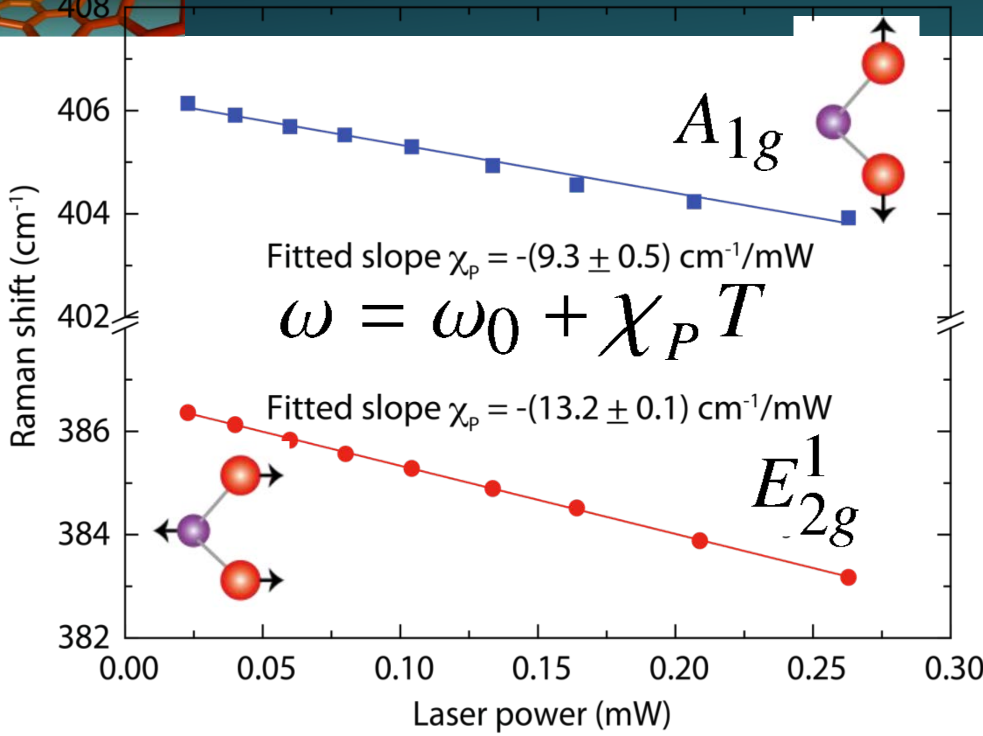
λ_{ex} = 488 nm

100X NA 0.95

~ 0.7 μm diffraction-limited spot

- Room temperature measurement
- local heating **softens** phonon peak frequency
- sample damage for power > 2mW

Laser Power-Induced Phonon Peak Shifts



MoS_2	χ_p (cm^{-1}/mW)	
	E_{2g}^1	A_{1g}
1L suspended	**-13.2**	**-9.3**
1L supported[1]	-0.09	-0.40

[1] R. Yan *et al.*, arXiv:1211.4136

Graphene	χ_p (cm^{-1}/mW) G-band E_{2g}
1L suspended [2]	-1.3
1L supported [3]	-0.7

[2] Balandin *et al.*, Nano. Lettt. **8**, 902 (2008)
[3] Lee *et al.*, PRB **83**, 081419 (2011)

- Linear at low power, saturates above 0.3 mW (not shown)
- A_{1g} less sensitive to power
- substrate serves as heat sink
- 10x larger χ_P coefficient than graphene

Optical Absorption in Monolayer MoS2

Thermal conductivity $\kappa = \dfrac{A}{2\pi t}\dfrac{\partial P}{\partial T}$

$n_0 = 1$

suspended MoS2

$n_1 = 1 - 5i$

$n_2 = 1$

Model suspended 1L with complex index of refraction n_1 = 5 – i surrounded by air obtain transmittance *T* & reflectance *R*

$$\mathcal{T} = \left|\frac{t_{01}t_{12}\,\mathrm{e}^{i\phi_1}}{1 - r_{10}^2\,\mathrm{e}^{2i\phi_1}}\right|^2 \qquad t_{01} = \frac{E_t}{E_i}$$

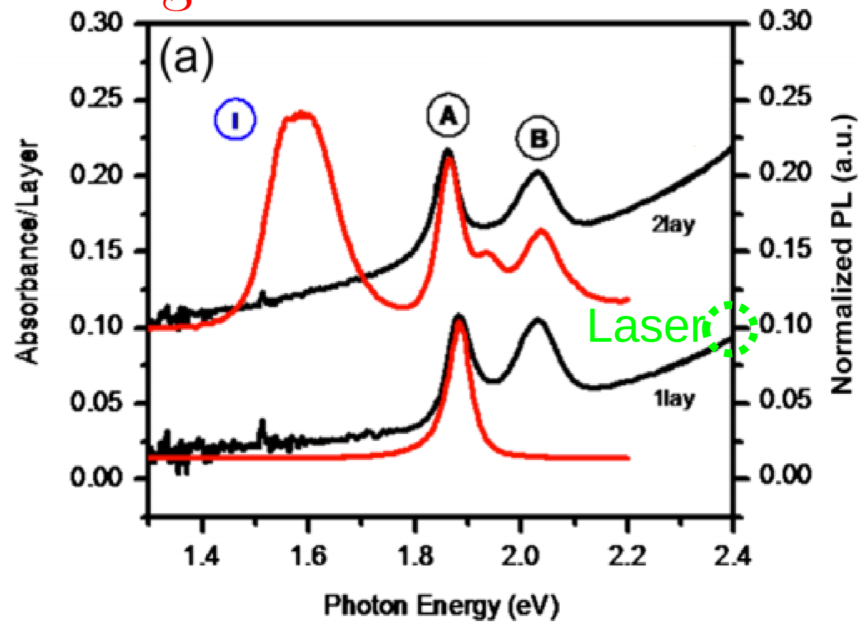
$$\mathcal{R} = \left|\frac{r_{01}\left(1 - \mathrm{e}^{i2\phi_1}\right)}{1 - r_{10}^2\,\mathrm{e}^{i2\phi_1}}\right|^2 \qquad r_{01} = \frac{E_r}{E_i}$$

$$\phi_1 = 2\pi\,\tilde{n}_1\,\nu\,d_1$$

<u>absorbance</u>: $A = 1\text{-}(R+T) = 0.09$
use this for determining incident laser power absorbed by sample

Beal & Hughes, JPC: Sol State Phys (1979)

agrees with measurement

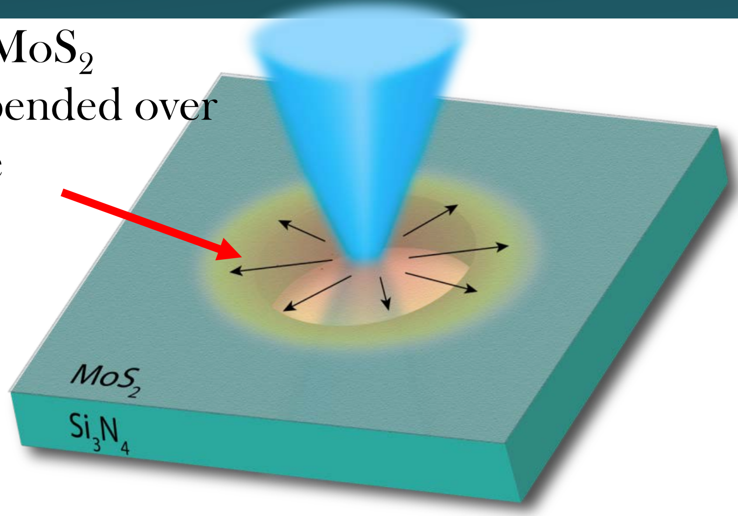


Mak *et al.*, PRL **105**, 136805 (2010)

Estimating Thermal Conductivity

Thermal conductivity

$$\kappa = \frac{A}{2\pi t}\frac{\partial P}{\partial T}$$



Rewrite κ in terms of phonon shifts linear temperature & power coefficients, χ_T & χ_P

$$\kappa = \frac{A}{2\pi t}\frac{\partial P}{\partial \omega}\frac{\partial \omega}{\partial T} = \frac{A}{2\pi t}\frac{\left(\frac{\partial \omega}{\partial T}\right)}{\left(\frac{\partial \omega}{\partial P}\right)}$$

$$\kappa = \frac{A}{2\pi t}\frac{\chi_T}{\chi_P}$$

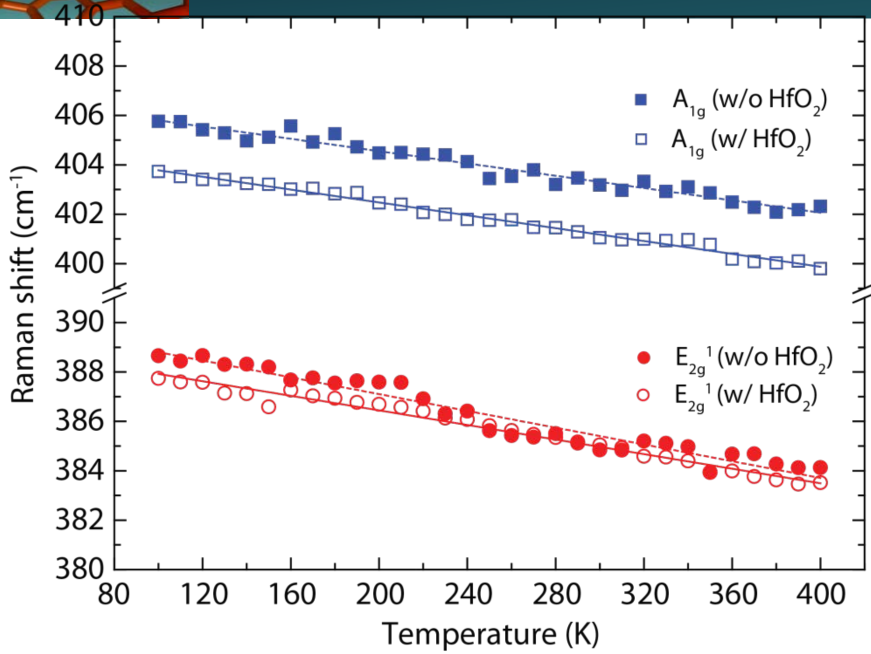
thermal conductivity κ from measured χ values

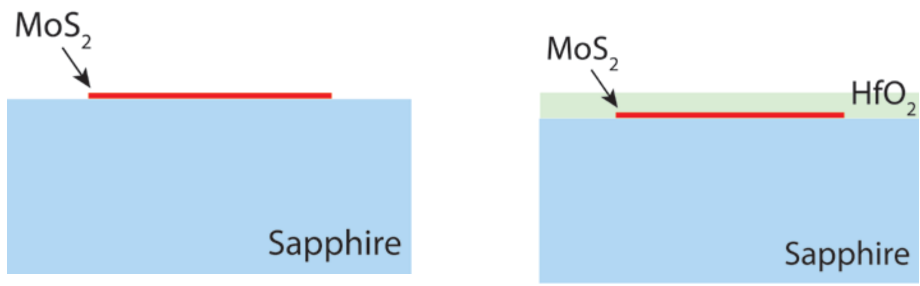
Suspended single layer	κ W/(m K)
MoS_2	27 +/- 20% *
graphene[1]	5000

[1] Balandin *et al.*, Nano Lett. **8**, 902 (2008).

* A_{1g} dominates κ in MoS_2

Substrate-Supported 1L MoS_2





MoS_2	χ_T (cm^{-1}/mW) E_{2g}^1		A_{1g}
w/ HfO_2	-0.017	>	-0.013
w/o HfO_2	-0.015	>	-0.013
suspended	-0.011	<	-0.014

Thermal expansion: Sapphire :7.3x10^{-6}/K
HfO_2: 6.7x10^{-6}/K
Bulk MoS_2 (in plan): 4.9x10^{-6}/K

- Al_2O_3 & HfO_2 similar thermal expansion & larger than bulk MoS2 → tensile strain

  Sapphire :7.3x10^{-6}/K, HfO_2: 6.7x10^{-6}/K

  Bulk MoS_2 (in plane): 4.9x10^{-6}/K

- HfO_2 induces A_{1g} shift → electronic doping[1,2]
- Consistent with theoretical prediction: A_{1g} more sensitive to el-ph coupling[1]

1. B. Chakraborty et al., PRB 85, 161403(R) (2012).
2. R. Yan et al., arXiv:1211.4136.

Conclusions

Raman continues to be a novel characterization methods for nanoelectronics

Thank you for you attention….

Thanks the people who do the work

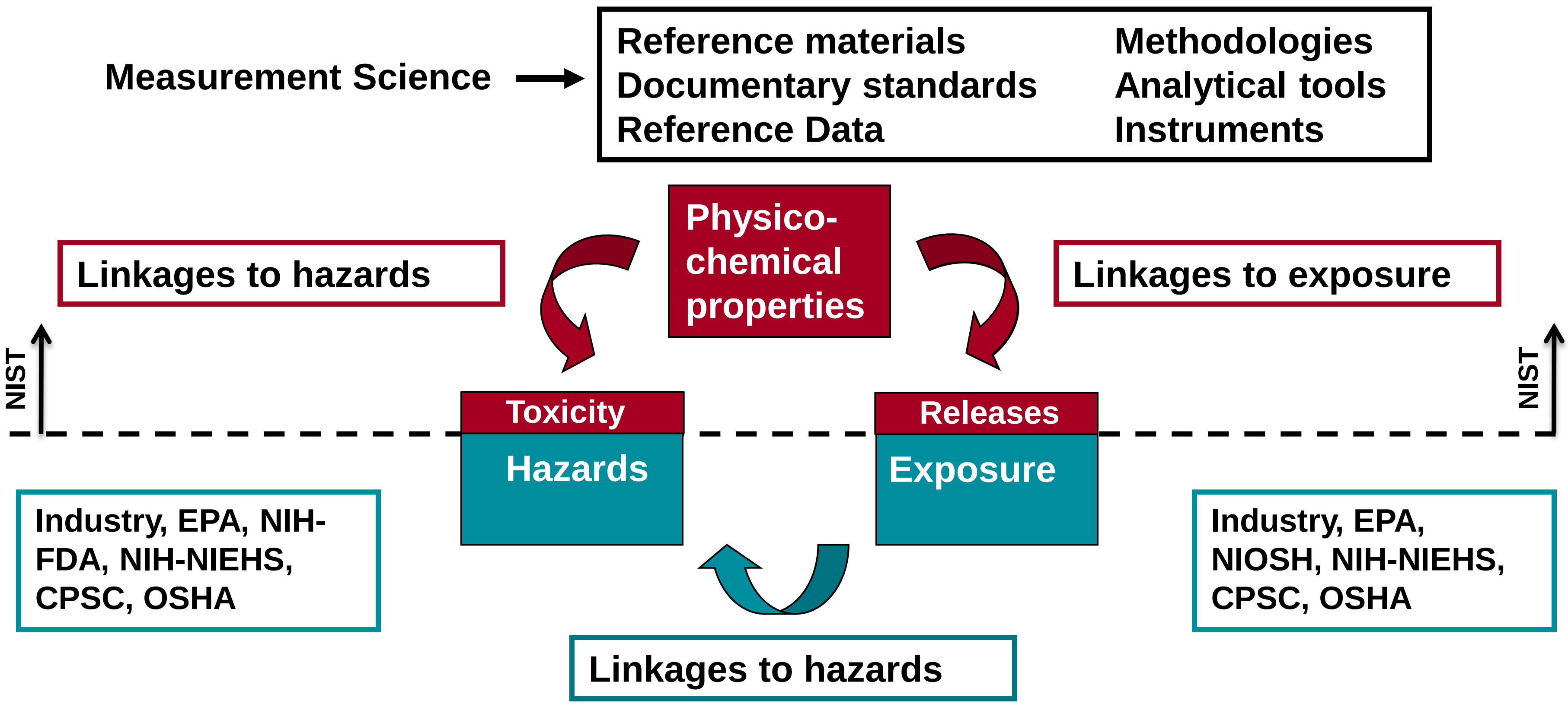
Problem and Solution

Nanomaterials and products that incorporate nanomaterials **pose** ***unknown risks*** throughout all stages of their life cycles, from initial sourcing through manufacture, use, disposal or recycling, and ultimate fate.

Sets of accurate data for physico-chemical properties, hazards, and exposure to enable science-based, lifecycle risk assessment and risk management of nanomaterials and products that incorporate them.

NIST Role in the Solution

Create and disseminate critical measurement solutions for determining key *physico-chemical and toxicological properties of nanomaterials and release of nanomaterials* throughout the full life cycles of key nanomaterials and products containing these nanomaterials.



Nano-EHS Technical Program

Measurement Science →

Reference materials	**Methodologies**
Documentary standards	**Analytical tools**
Reference Data	**Instruments**

Static Physico-chemical Properties*

Concentration of neutral and ionic species of key nanomaterials

Surface attributes of key nanomaterials*:
- Surface area
- Composition, location, and degree of coverage of surface species
- Morphology from the atomic to cellular scales
- Surface charge

**Controlled dispersion is critical for all measurements*

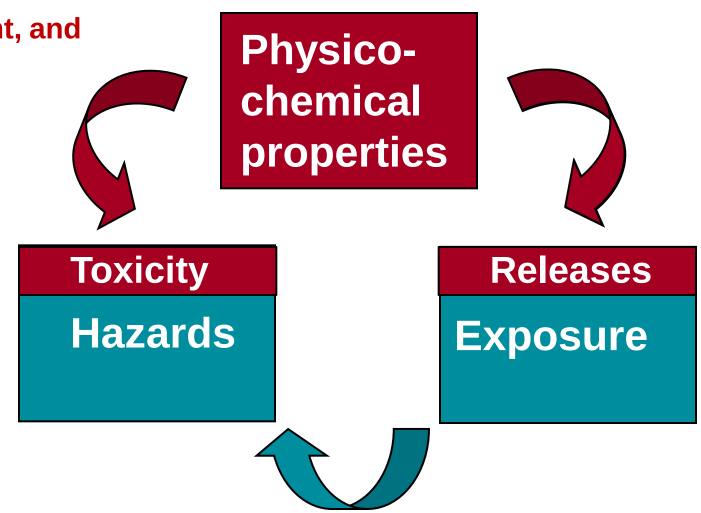
Dynamic Physico-chemical Properties*

Transformation processes for key nanomaterials*:
- Aggregation and agglomeration
- Ionic dissolution
- Adsorption of organic matter and bioconstituents
- Electron transport, *e.g.,* oxidation
- Attachment of nanomaterials to surfaces

Transport

Fate: equilibrium state, concentration, and distribution

***In relevant media: air, water, soil, sediment, and biological matrices**



Toxicological Properties*

Biomarkers and other indicators of toxicological response

Genotoxicity assays

Mechanistic cytotoxicity assays

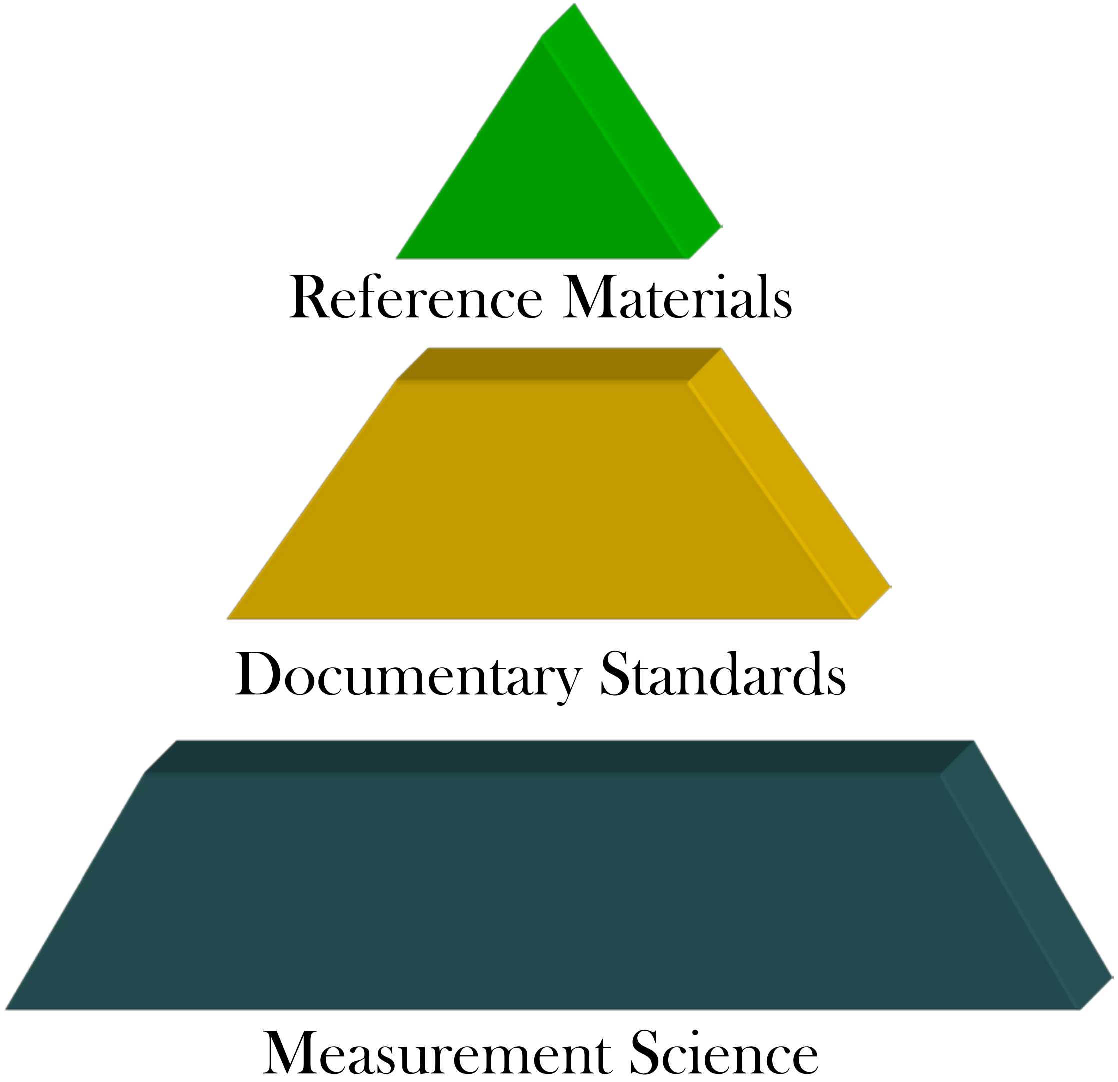
Exposure effects*

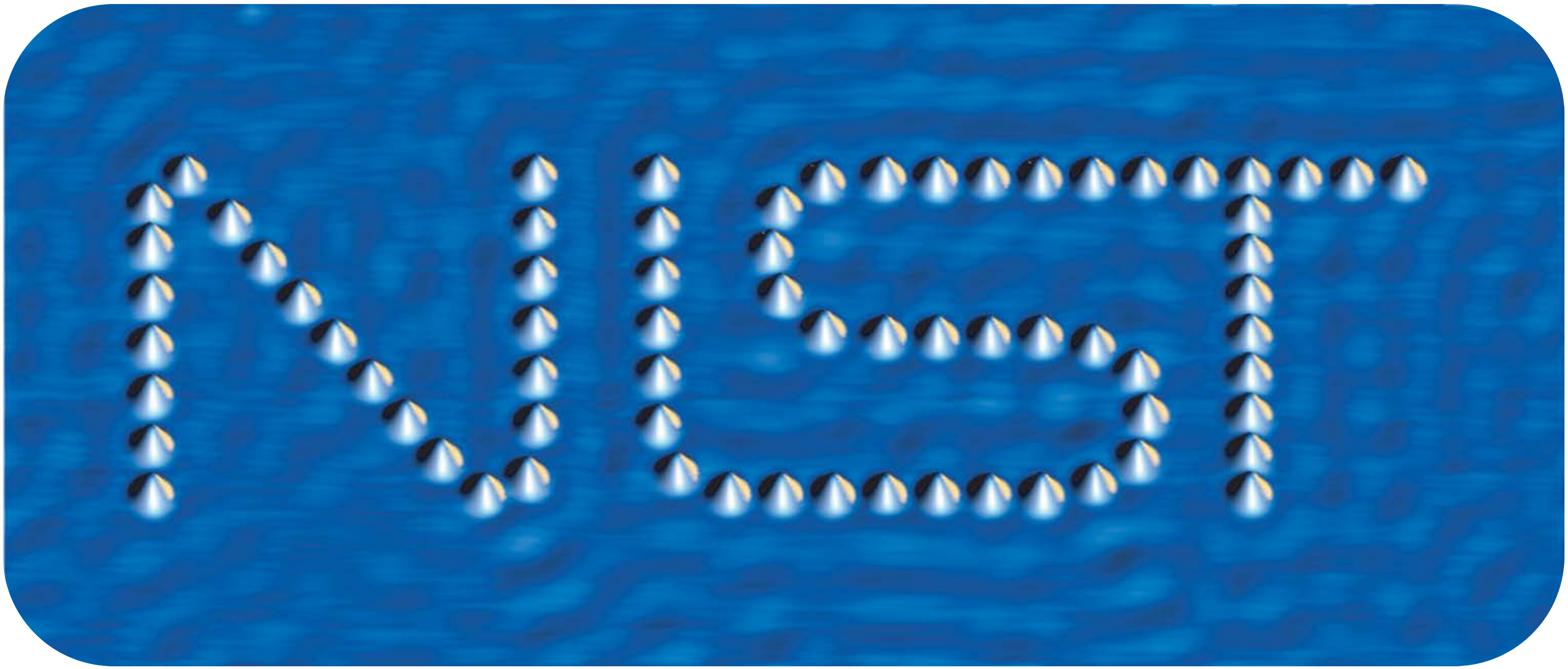
Release of key nanomaterials from products
- Incineration
- Wear
- Chemical reactions

Emissions from manufacturing processes

NIST

Optimal Approach





Thank you!!