Putting Things on Top of Other Things: Assembly of Graphene and Carbon Nanotube Devices by Mechanical Transfer

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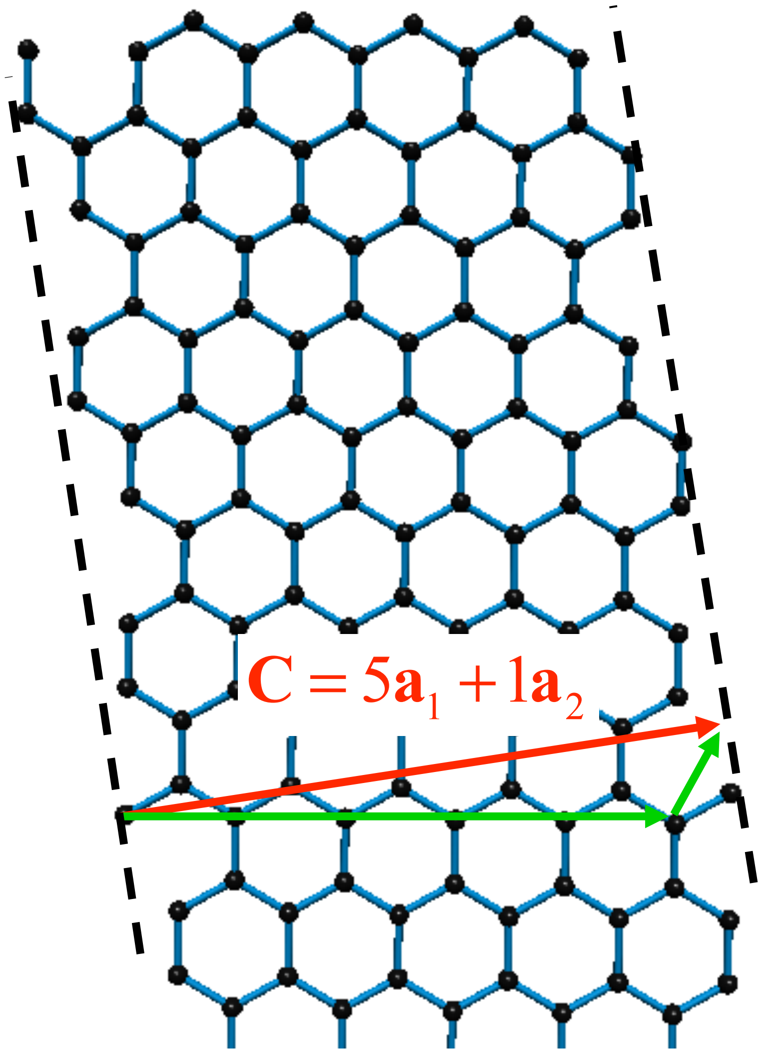
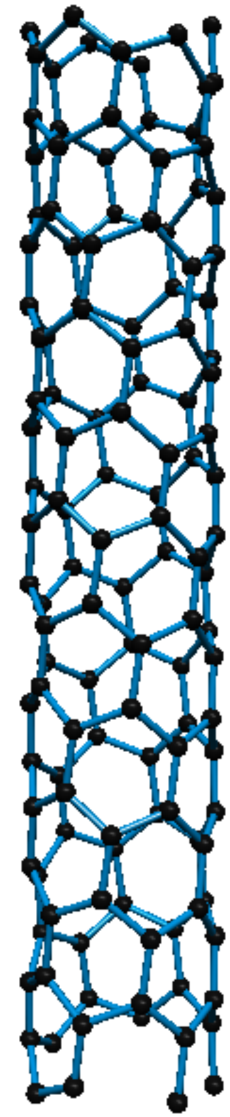
Nanotubes: Crystal Structure



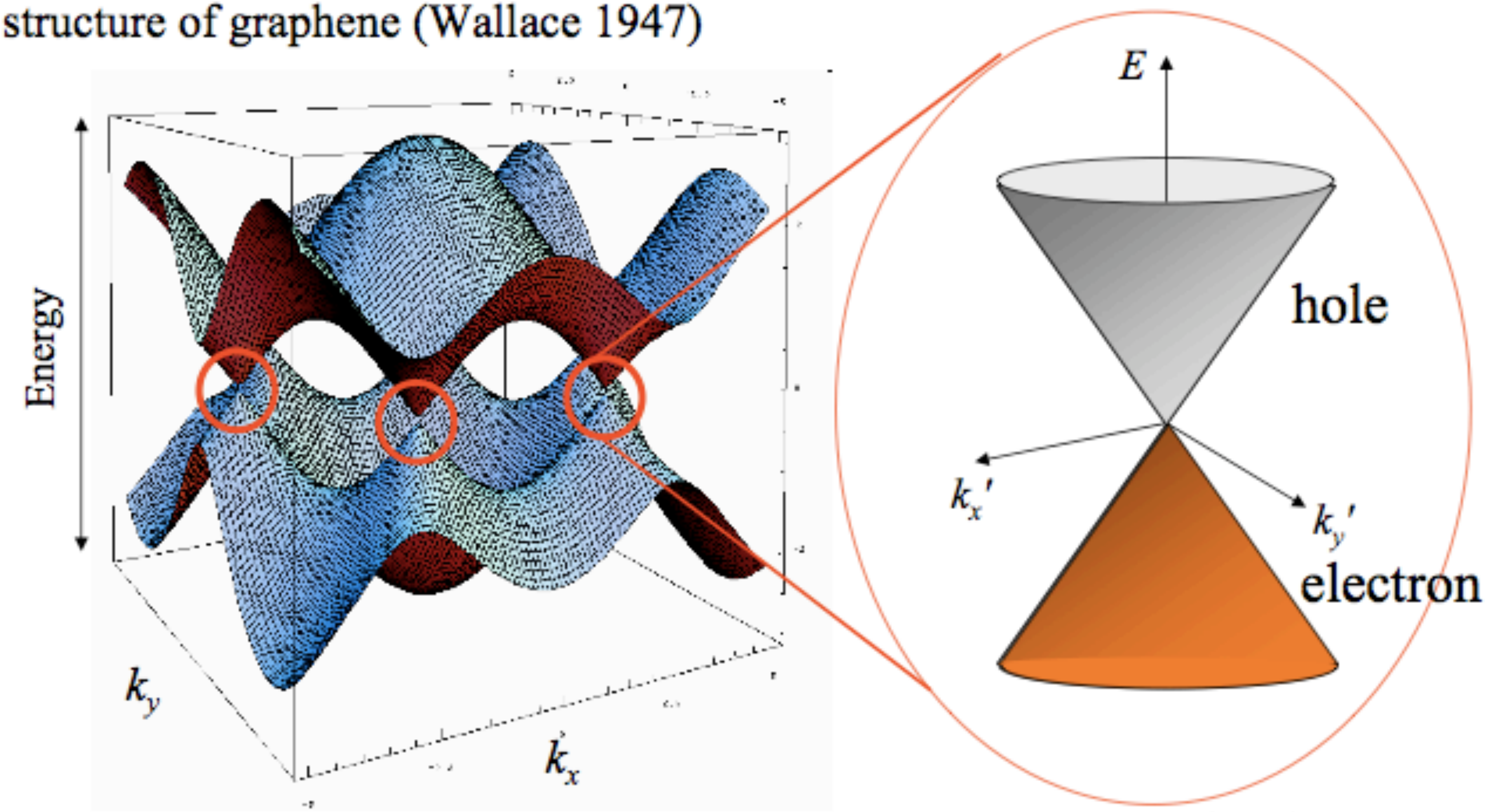
(5,1) SWNT

(n,m) chiral indices uniquely determine nanotube crystal structure



Physical and Electronic Structure

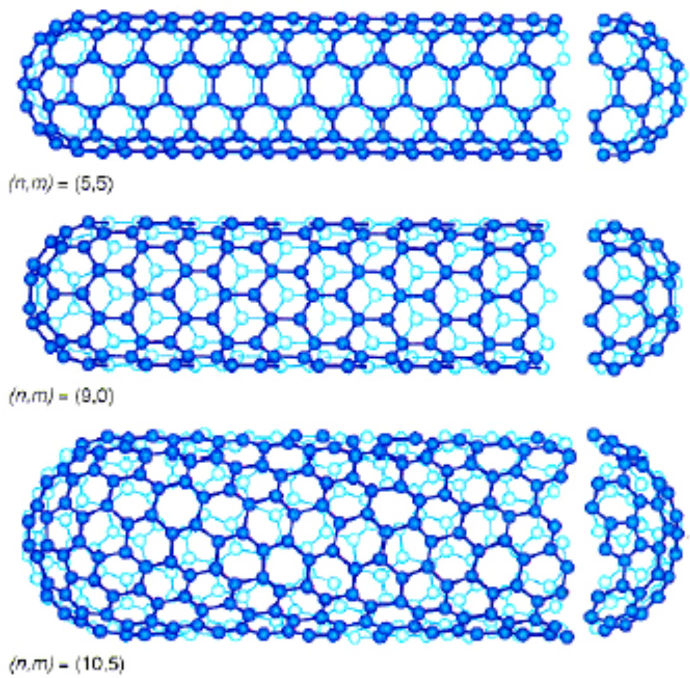
Band structure of graphene (Wallace 1947)

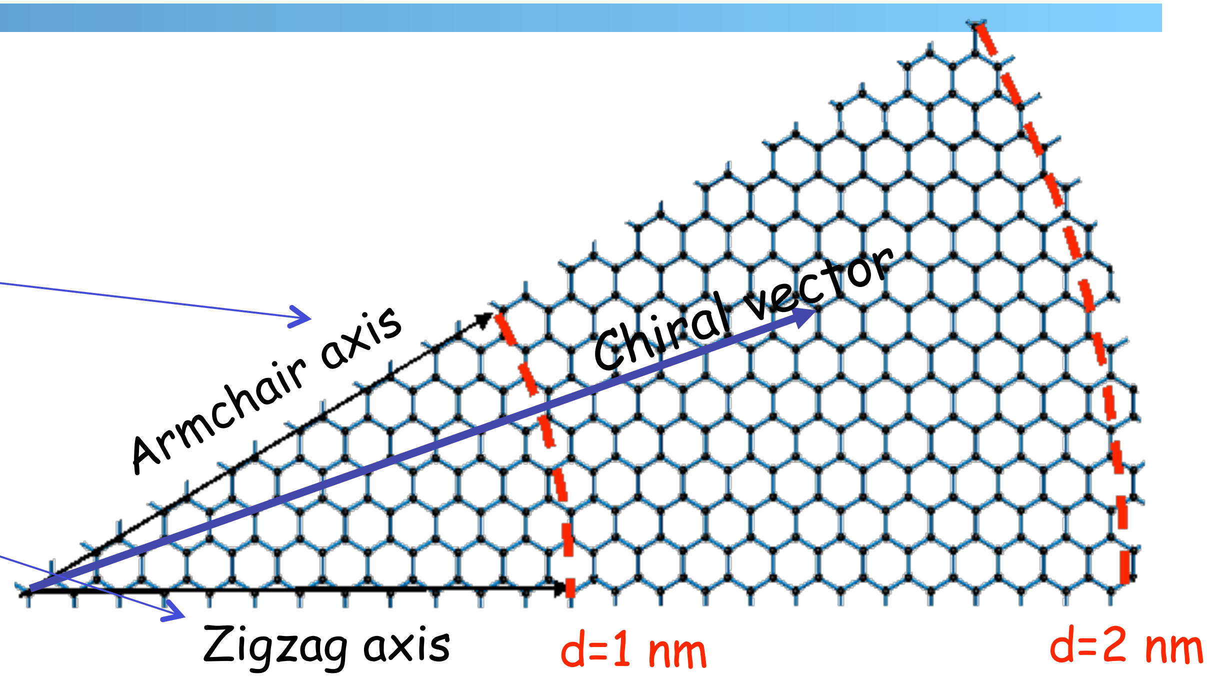


$$E \approx \hbar v_F \left| \vec{k}'_{\perp} \right|$$

Zero effective mass particles moving with a constant speed v_F

How many different structures?



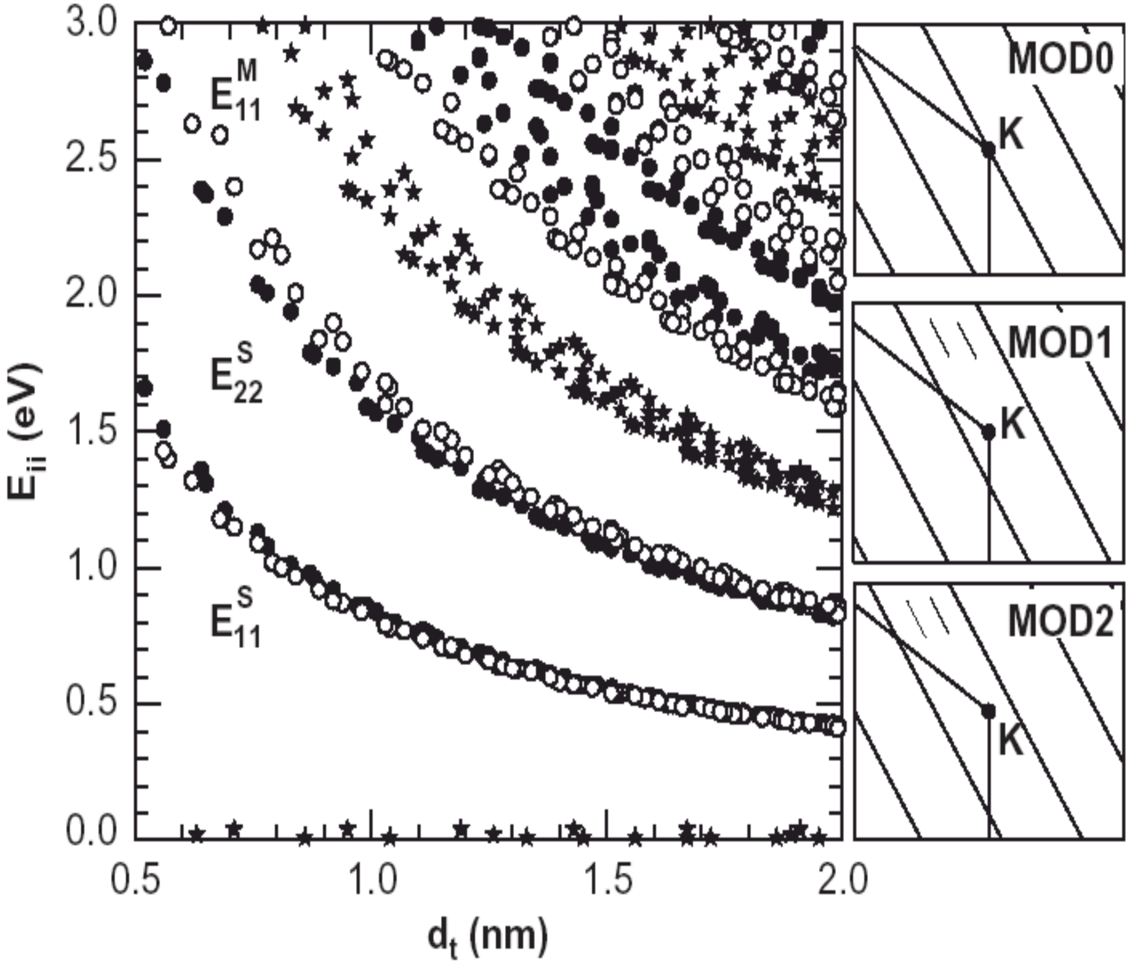


~200 nanotubes in 1-2 nm diameter range

2/3 semiconducting — Eg ≈ 800 meV/d(nm)

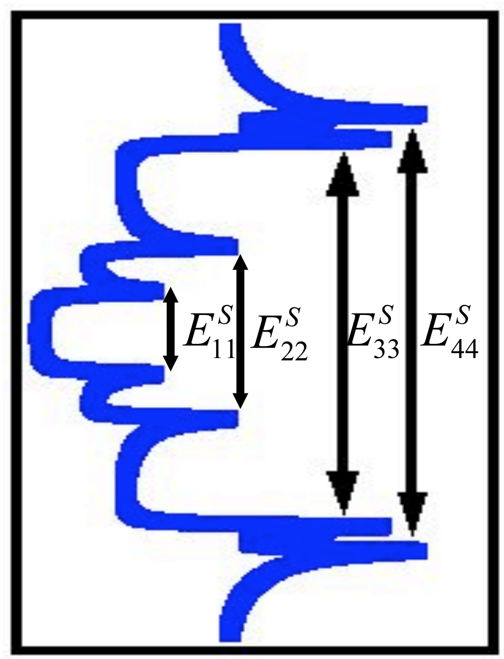
1/3 metallic
- → (n,n) armchair Eg=0
- → n ≠ m 'chiral metal' Eg ≈ 5-20 meV

Identifying the Crystal Structure

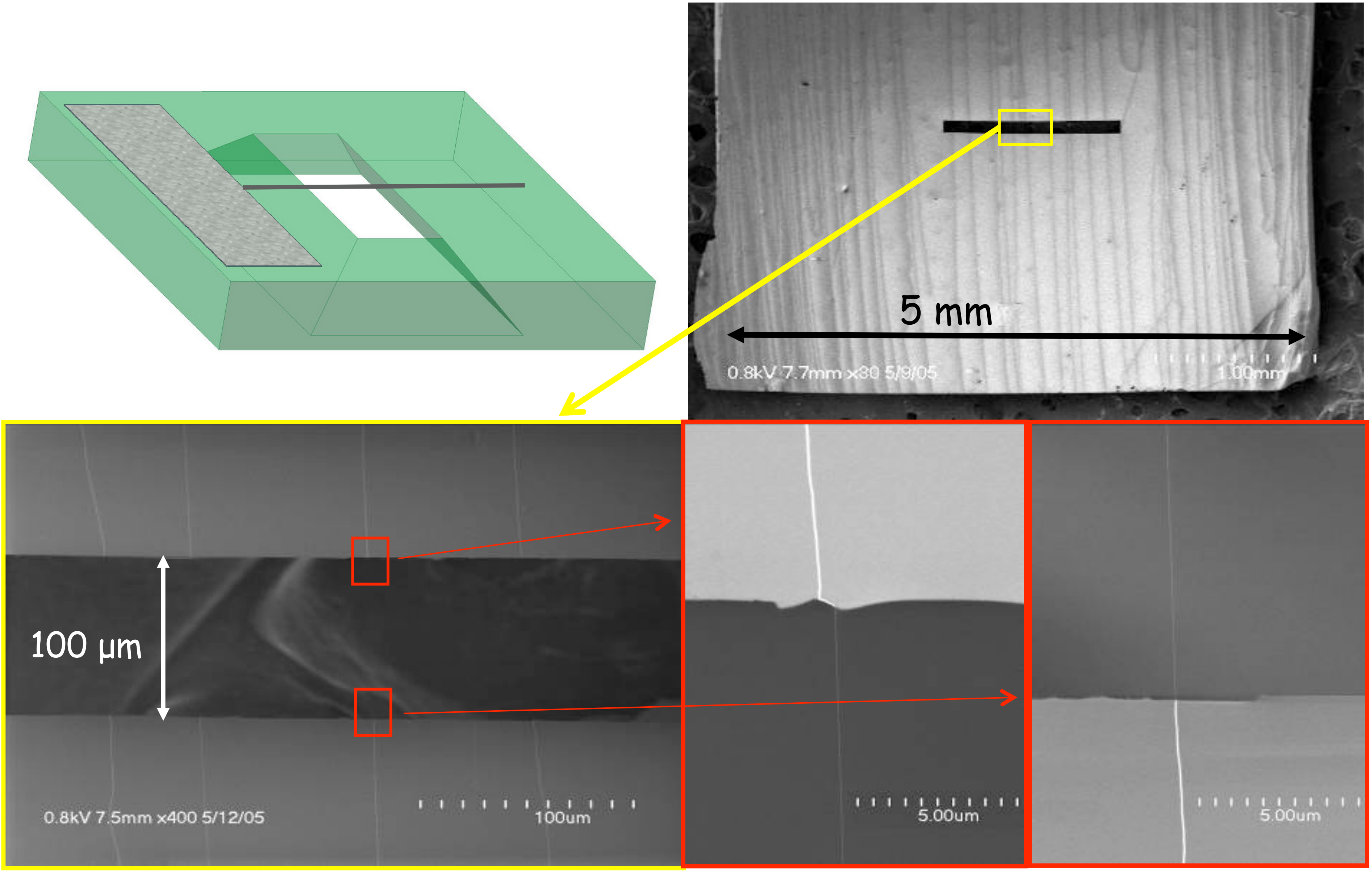


allowed optical transitions for nanotubes in the 0.5-2 nm diameter range

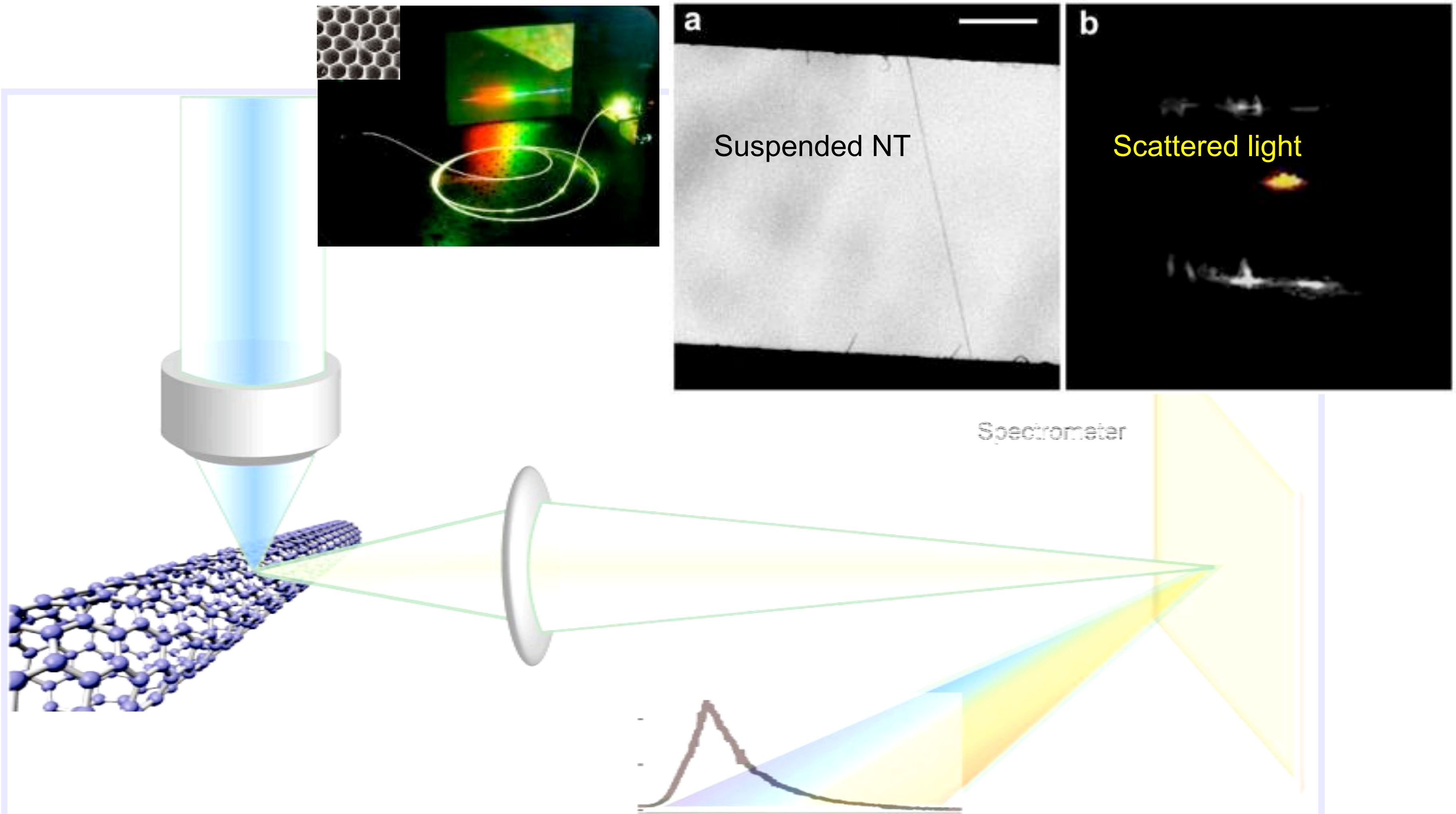
Series of optical transitions should provide a unique fingerprint for each nanotube



Suspended Nanotubes for Single-Tube Spectroscopy



Rayleigh Scattering Spectroscopy



Probing Electronic Transitions in Individual Carbon Nanotubes by Rayleigh Scattering

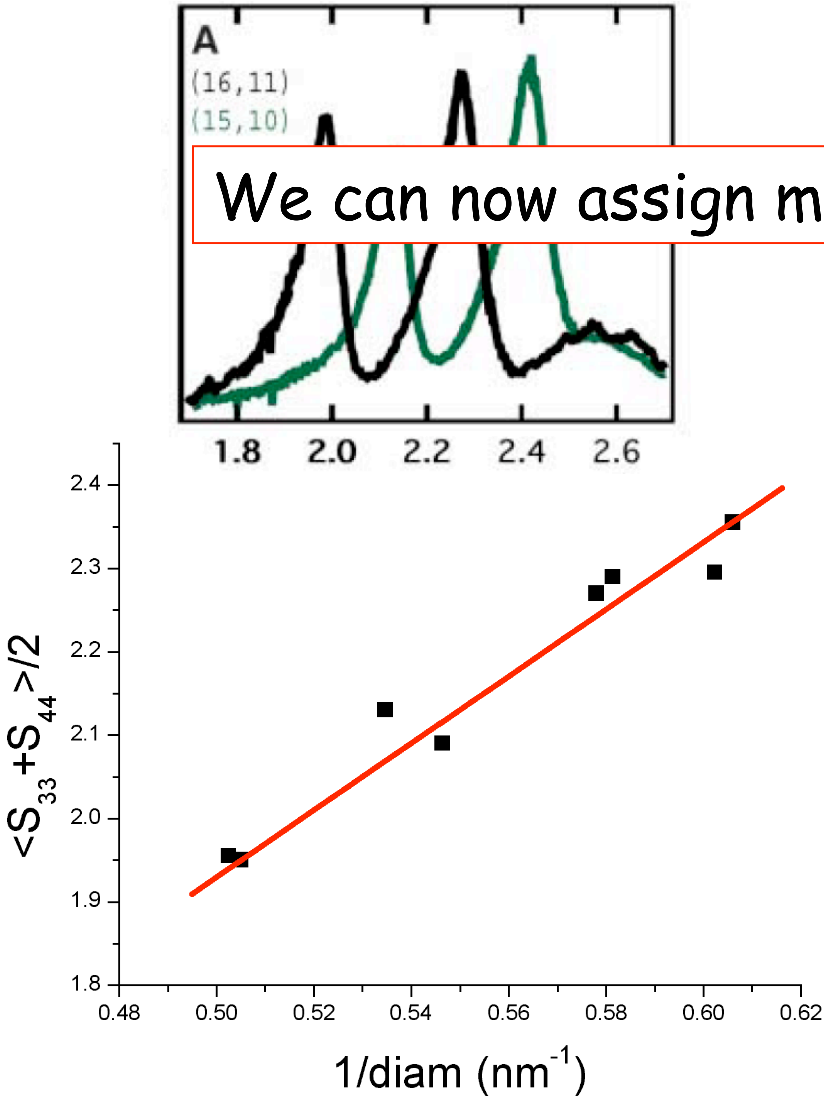
Matthew Y. Sfeir, Feng Wang, Limin Huang, Chia-Chin Chuang, J. Hone, Stephen P. O'Brien, Tony F. Heinz, Louis E. Brus

Science **306**, 1540-1543 (2004)

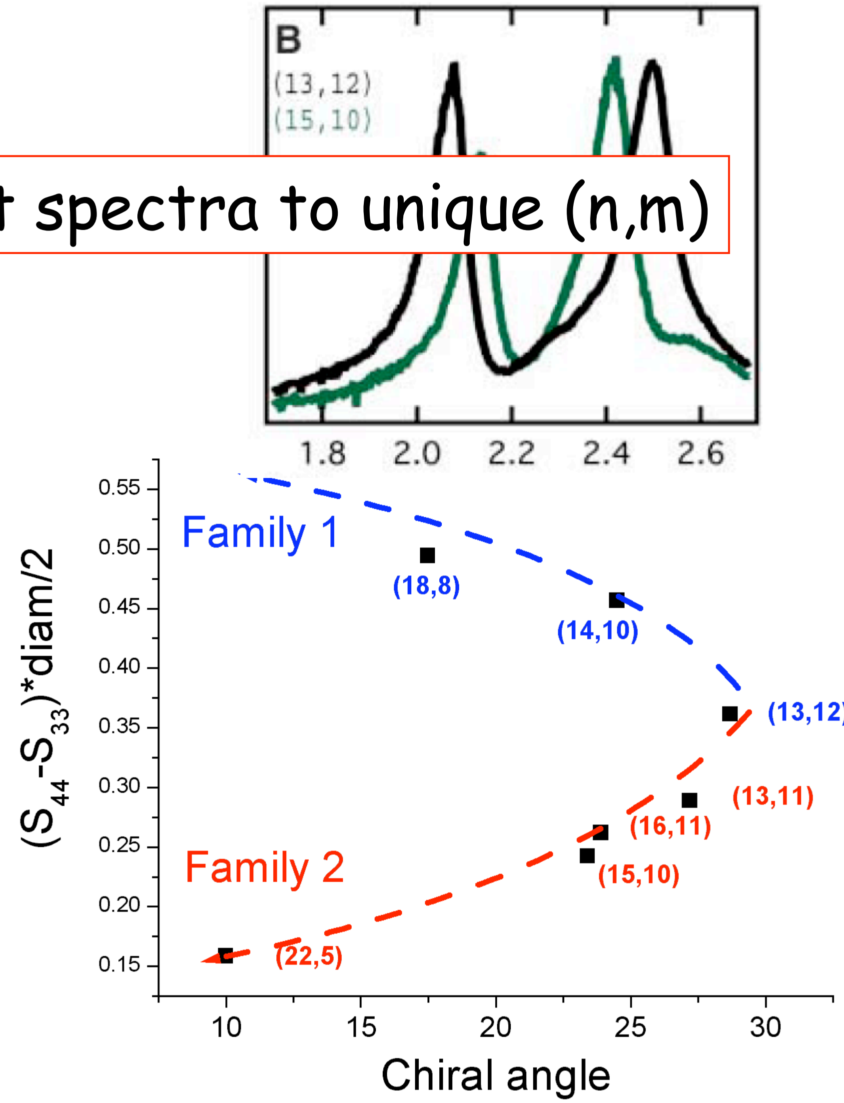
TEM Structural Assignment

Diameter Dependence

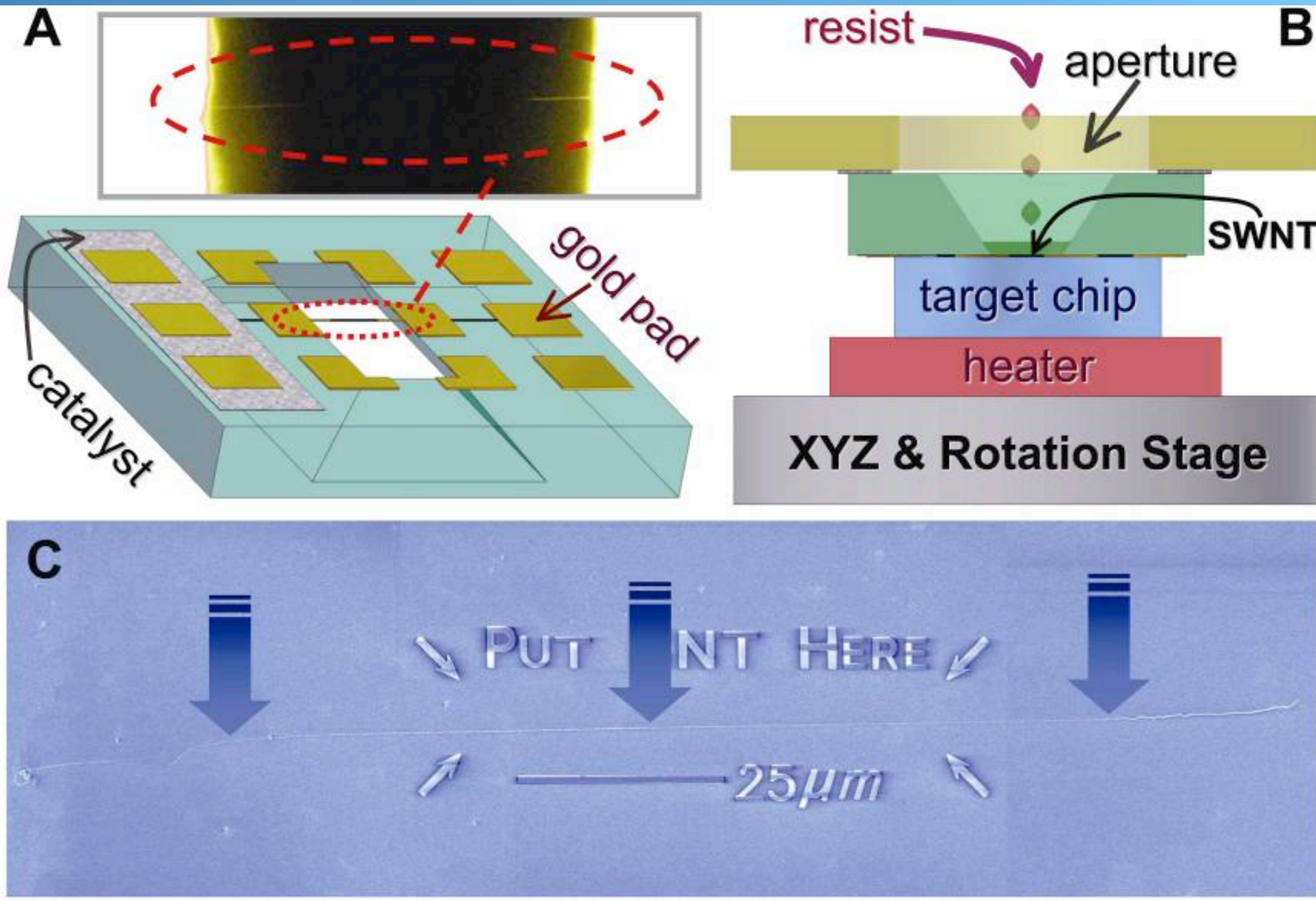
Chiral Angle Dependence



We can now assign most spectra to unique (n,m)

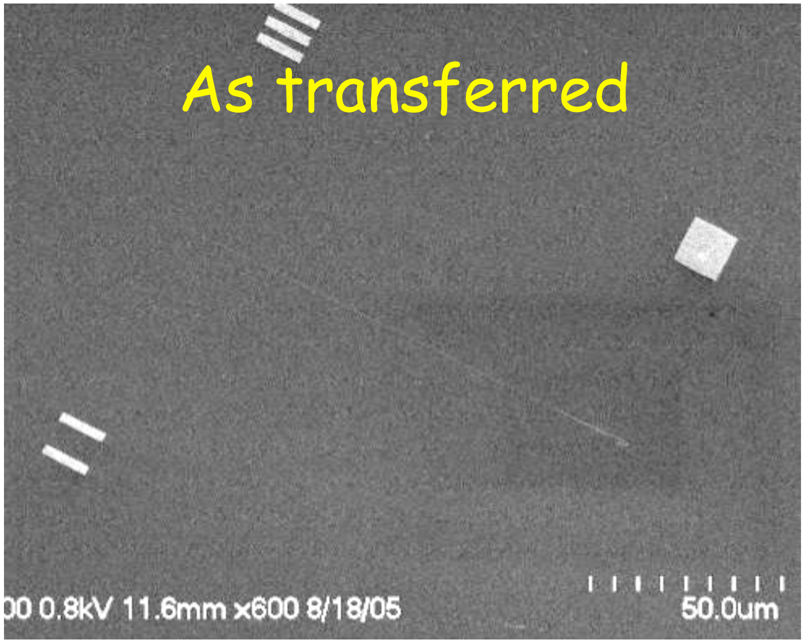


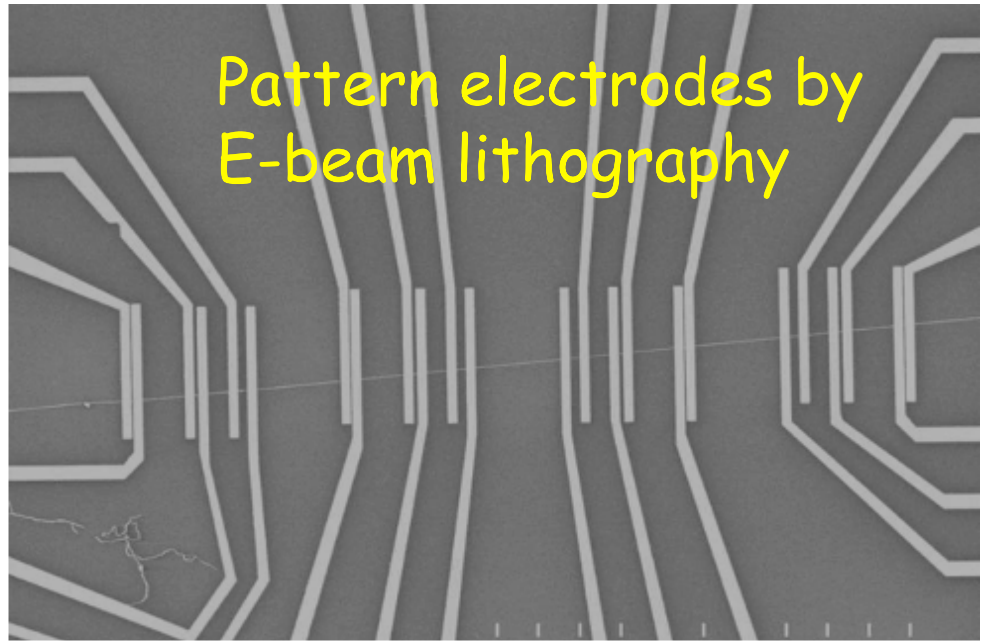
Nanotube Transfer for Electrical Measurements

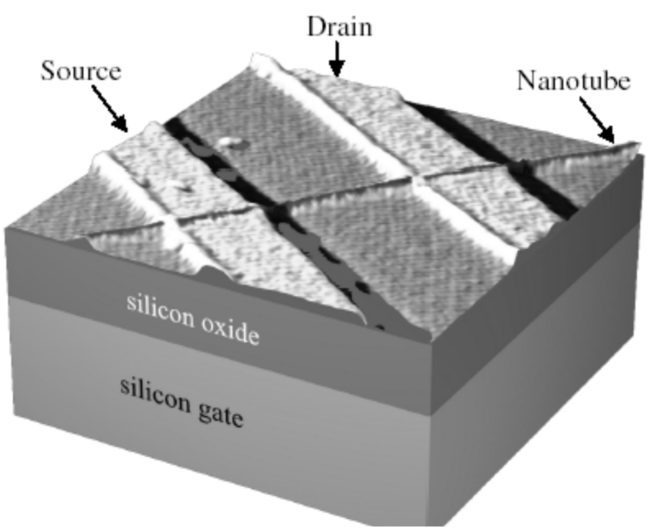


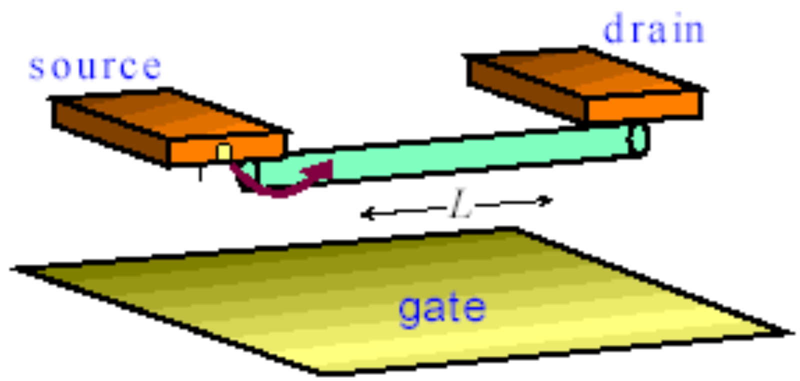
X.M.H. Huang, R. Caldwell, M. Huang, S.C. Jun, L. Huang, M. Sfeir, S. O'Brien, J. Hone. *Nano Letters* **5**, 1515-1518 (2005).

Transferred SWNT





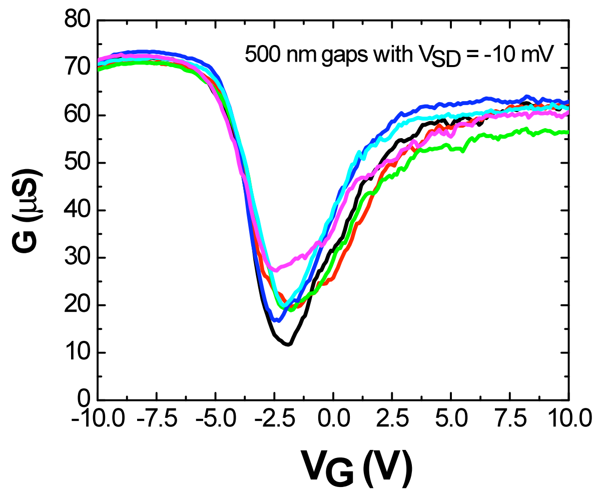


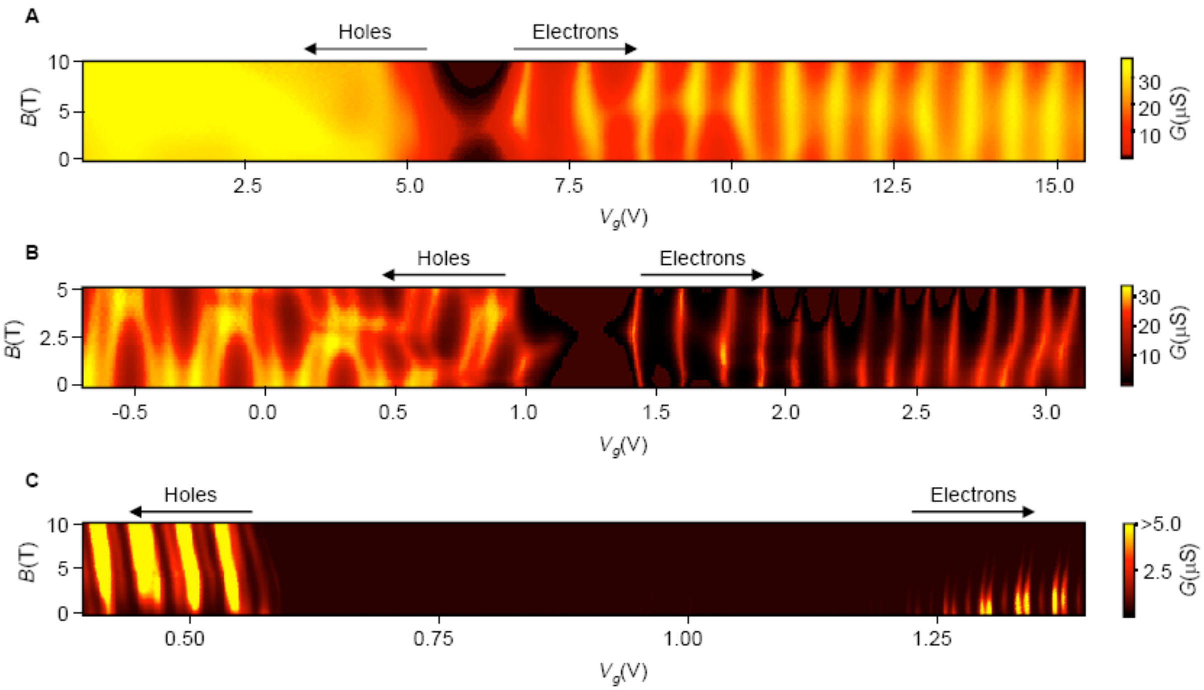


3-terminal electrical measurements

Are metallic tubes metallic?

'Armchair' tubes should be perfect metals… but we always see a 'gap'

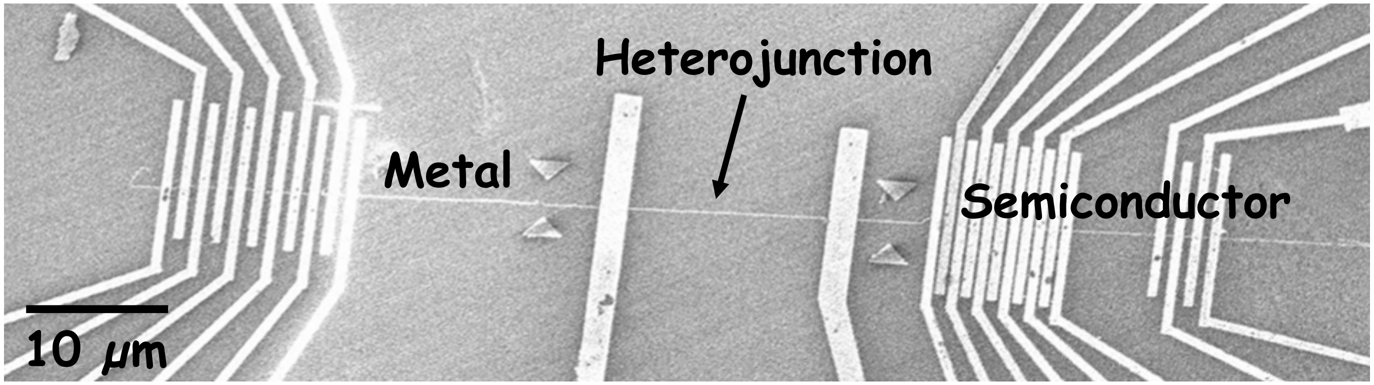


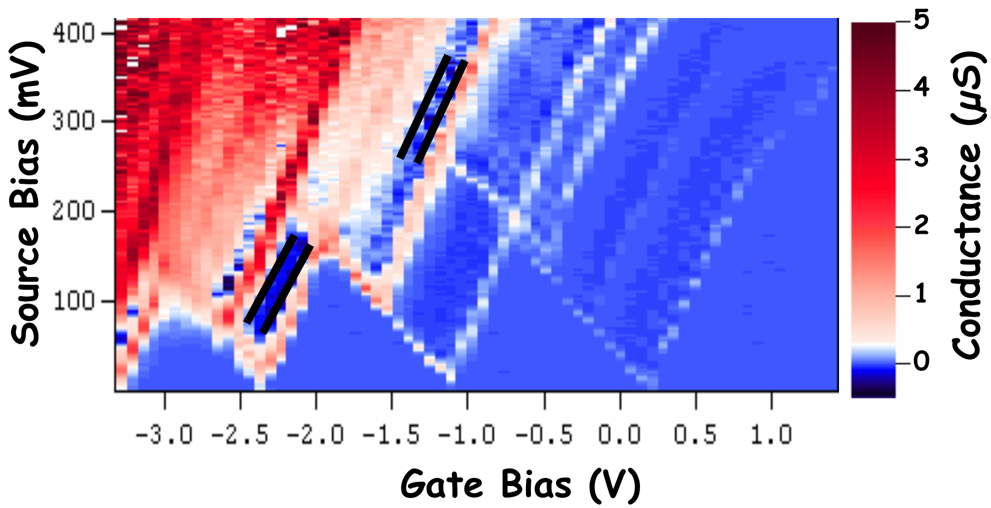


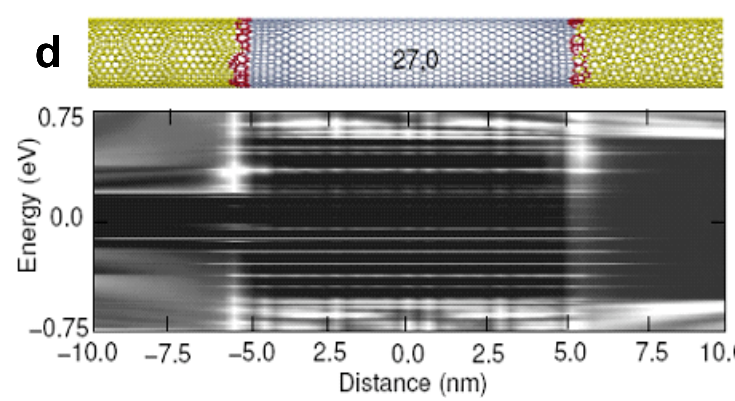
Explanation: electron-electron interactions cause insulating state at low charge density (Mott insulator). Highly unusual at room T!

Vikram V. Deshpande, Bhupesh Chandra, Robert Caldwell, Dmitry Novikov, James Hone, and Marc Bockrath, *Science* 323, 106 (2009).

Nanotube Heterojunction: Molecular Scale Quantum Dot

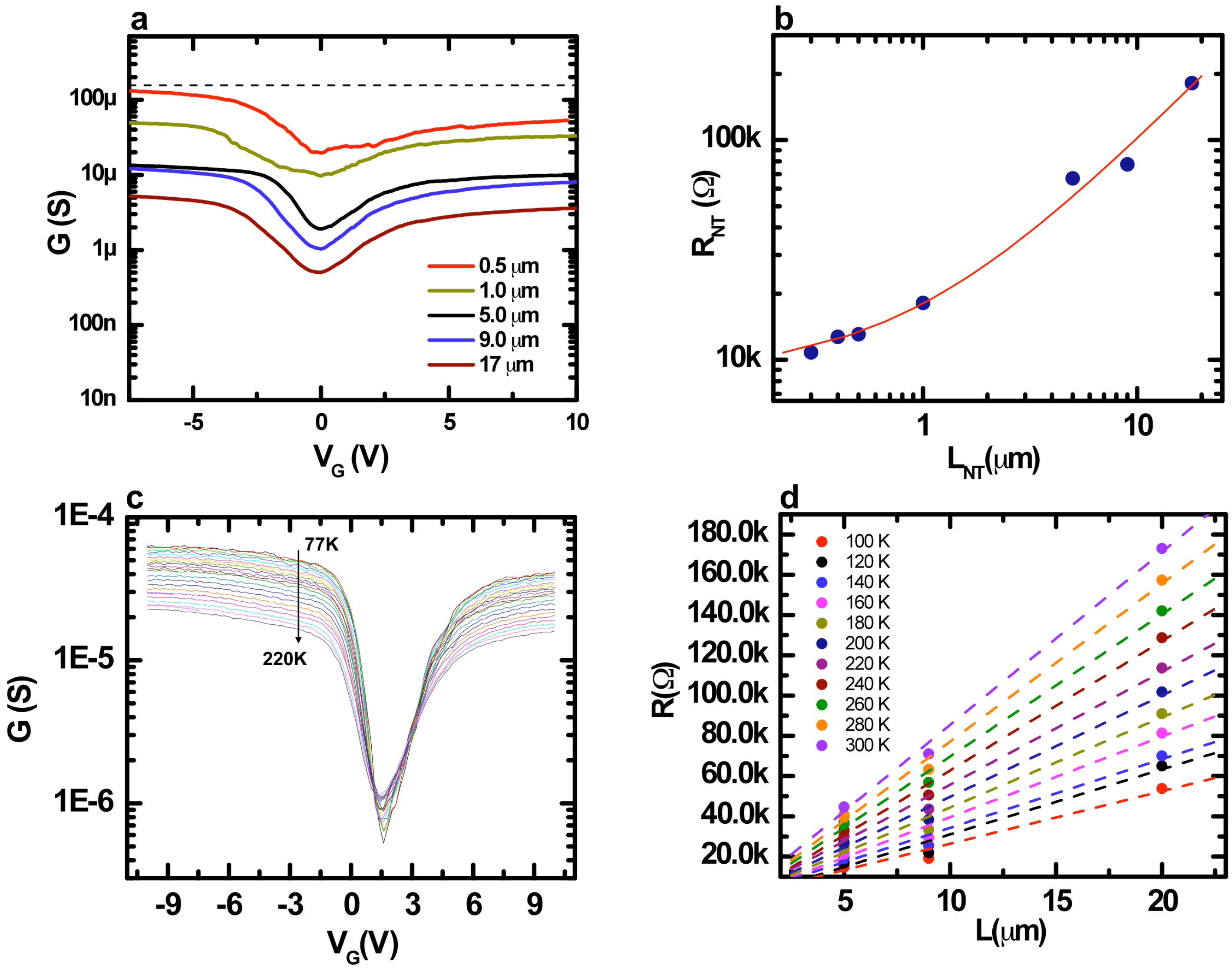






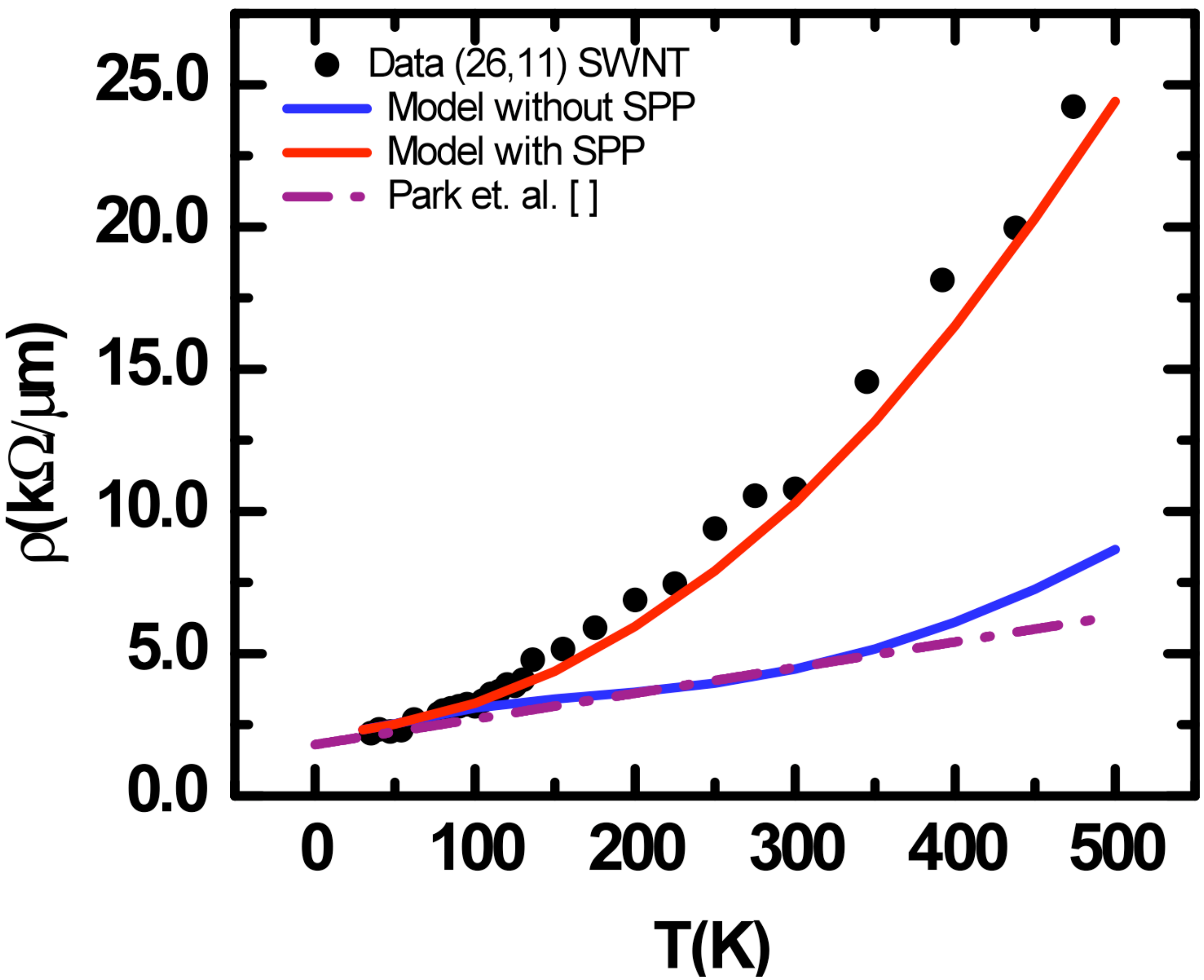
1. Bhupesh Chandra, Joydeep Bhattacharjee, Meninder Purewal, Young-Woo Son, Yang Wu, Mingyuan Huang, Hugen Yan, Tony F. Heinz, Philip Kim, Jeffrey. B. Neaton, James Hone, "Molecular-Scale Quantum Dots from Carbon Nanotube Heterojunctions," *Nano Lett.* **9**, 1544 (2009).

Resistivity of known-chiralty tube (26,11)



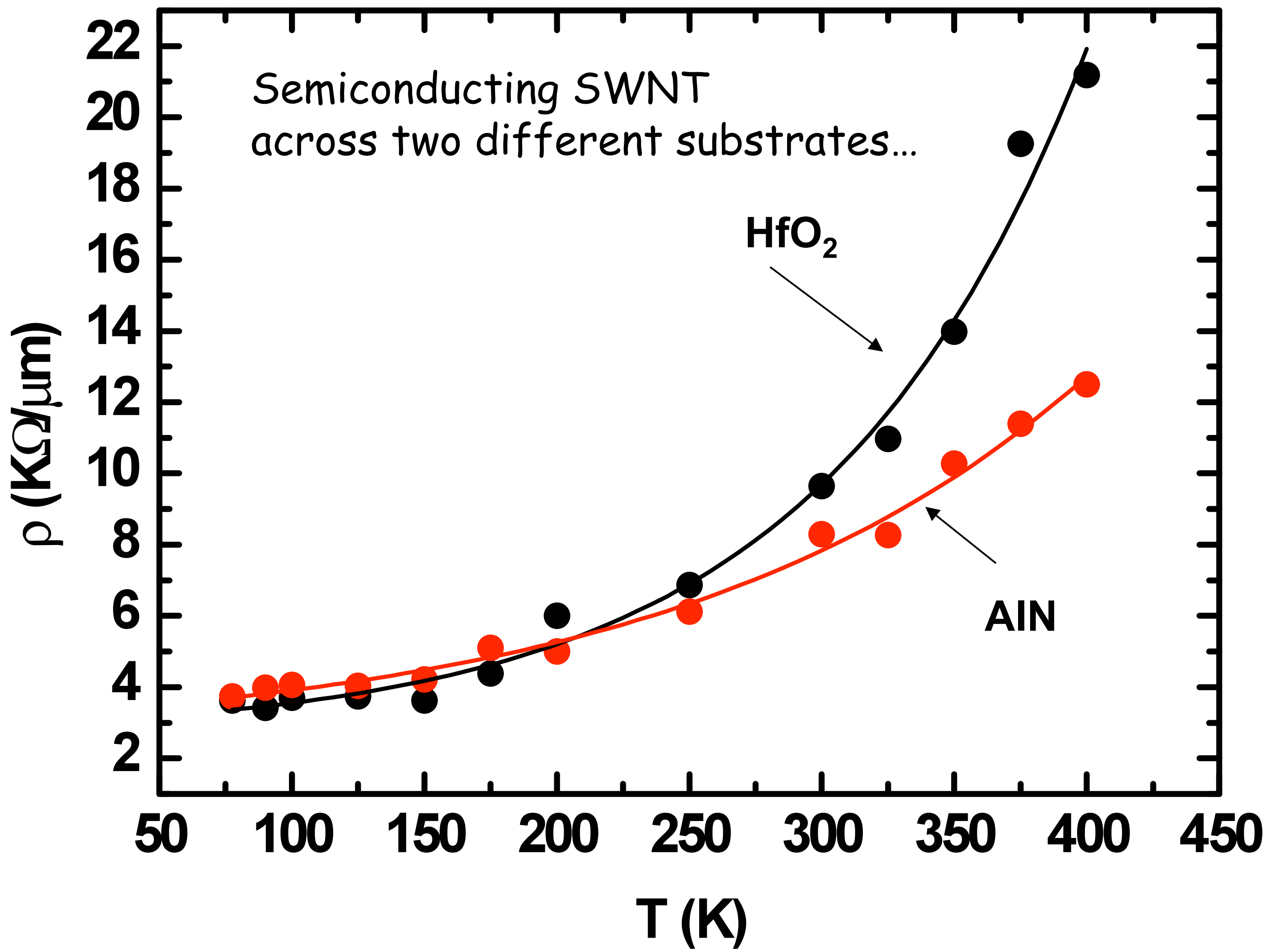
Bhupesh Chandra et al, submitted

Evidence for Substrate Effects



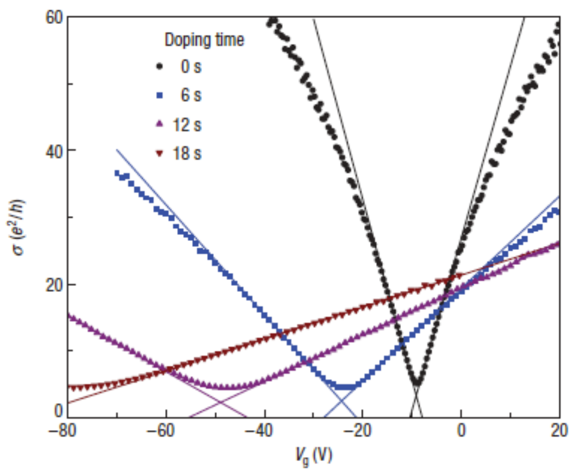
Surface Polar Phonons (SPP) are dominant scatterers at room T

Intrinsic and Extrinsic Resistivity

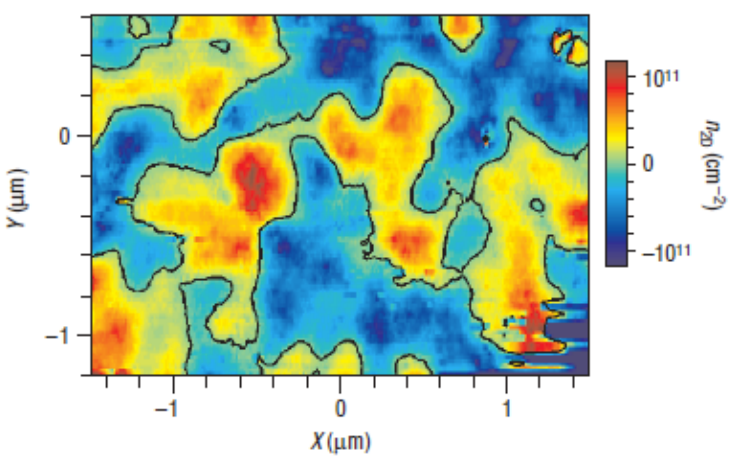


Boron Nitride Substrates for Carbon Electronics

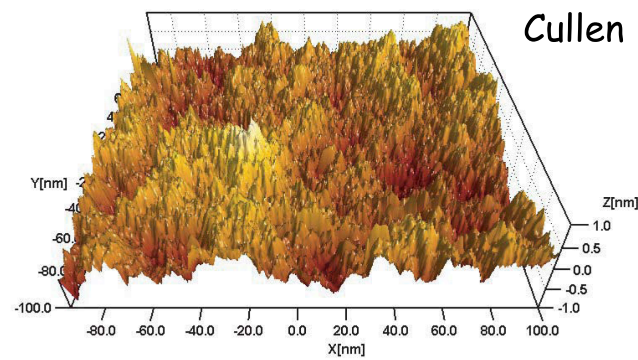
Transport in Carbon Electronics: Substrates are a Problem



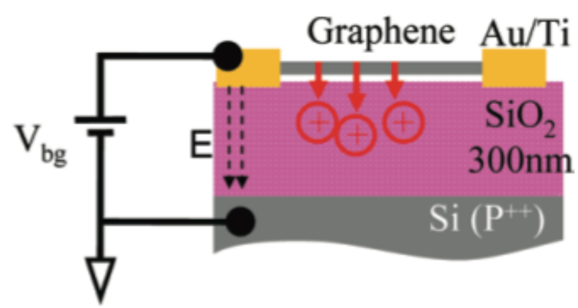
Chen *et al*, Nature Phys. (2008)



Martin, *et al*, Nature Phys. (2008)



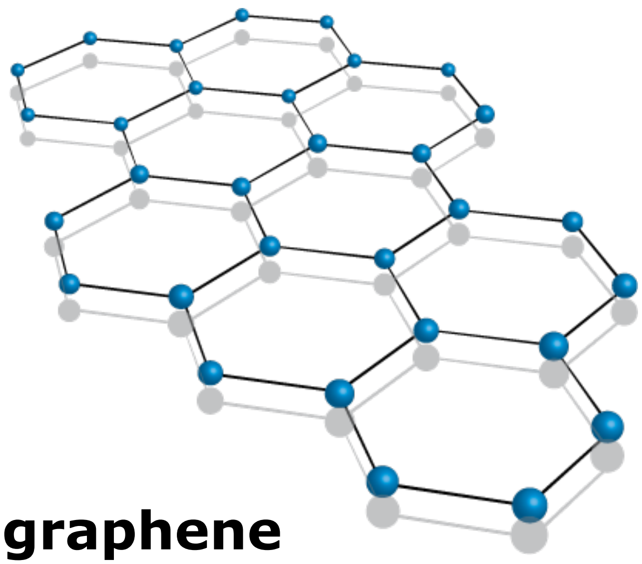
Cullen *et al*, PRL (2010)



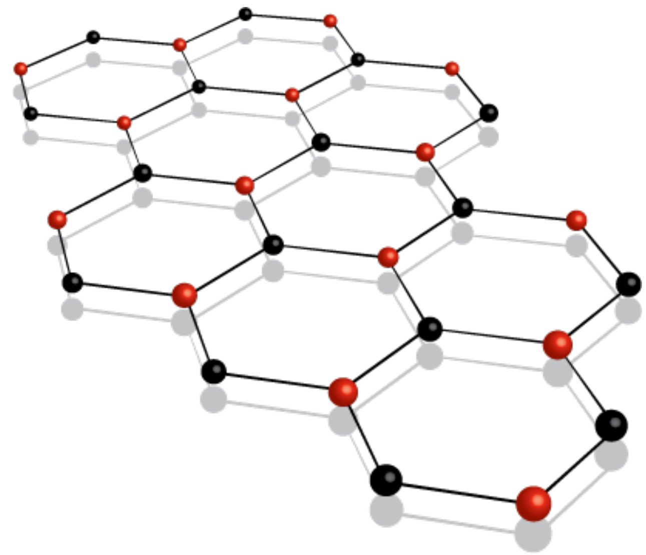
- mobility ~20,000 cm^2/Vs
- surface roughness
- charged impurity scattering
- potential disorder ~ 100 meV
- large hysteresis

Ando (2006); Nomura and MacDonald (2007);
Hwang, Adam and Das Sarma (2007)

Boron Nitride – An Ideal Dielectric for Carbon Electronics?



graphene

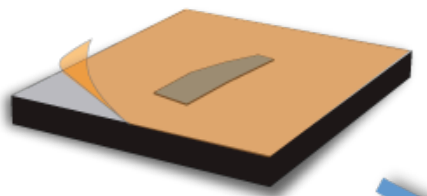


Hexagonal Boron Nitride

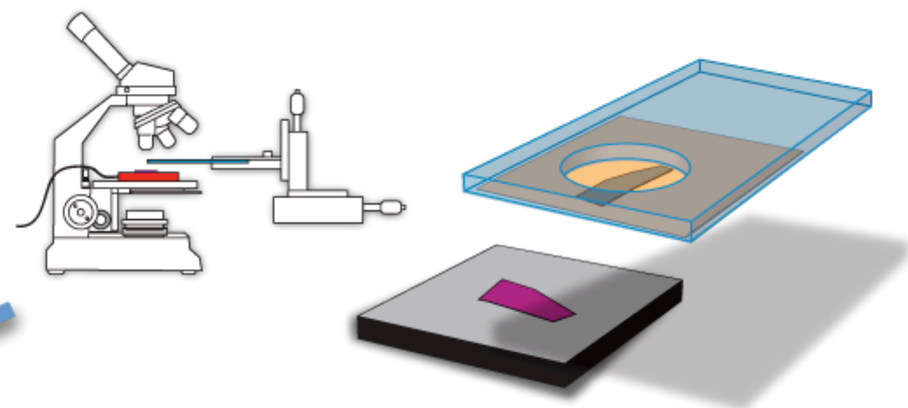
	Band Gap	Dielectric Constant	Optical Phonon Energy
BN	3.6 - 7.1 eV	~4*	>100 meV
SiO2	8.9 eV	3.9	59 meV

*measured in our lab

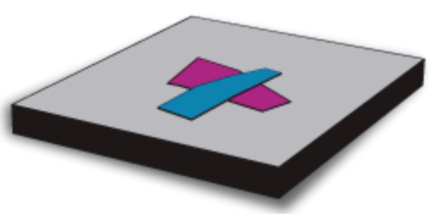
Graphene/BN transfer



1. spin coat substrate with PMMA and scratch onto top surface



2. Lift off PMMA; graphene comes with it!

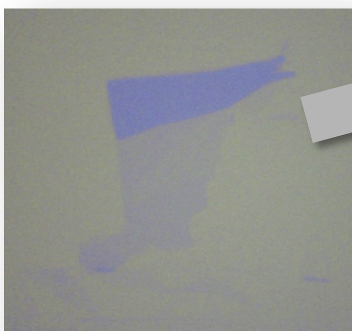


3. Align graphene over target using a micro-manipulator. PMMA is brought into contact with target and annealed.

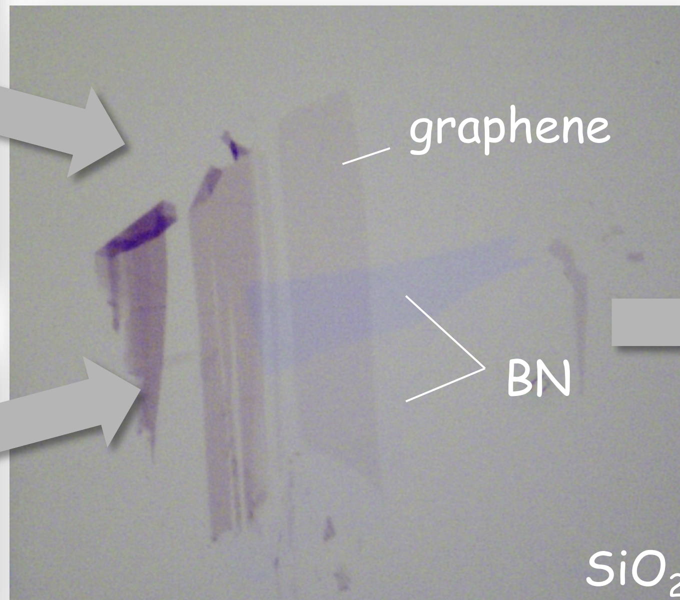
CC.R. Dean, A.F. Young, I. Meric, C. Lee, L. Wang, S. Sorgenfrei, K. Watanabe, T. Taniguchi, P. Kim, K.L. Shepard, J. Hone, Nature Nano (2010)

Graphene/BN transfer

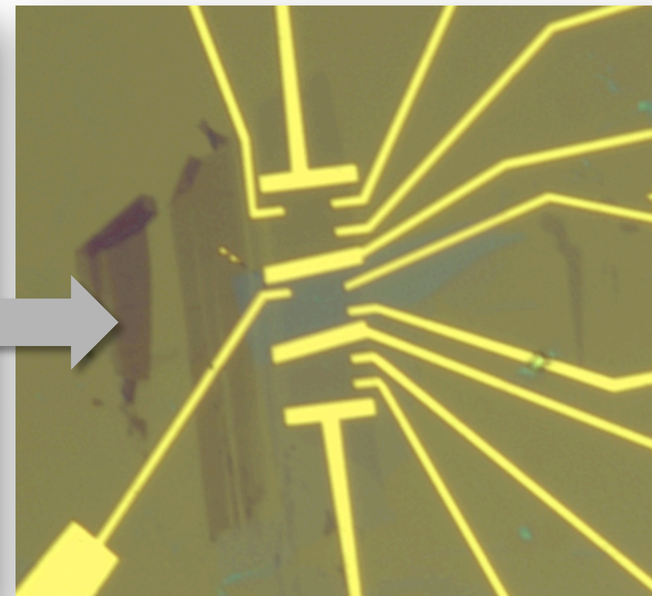
Graphene



BN



Graphene transferred onto BN

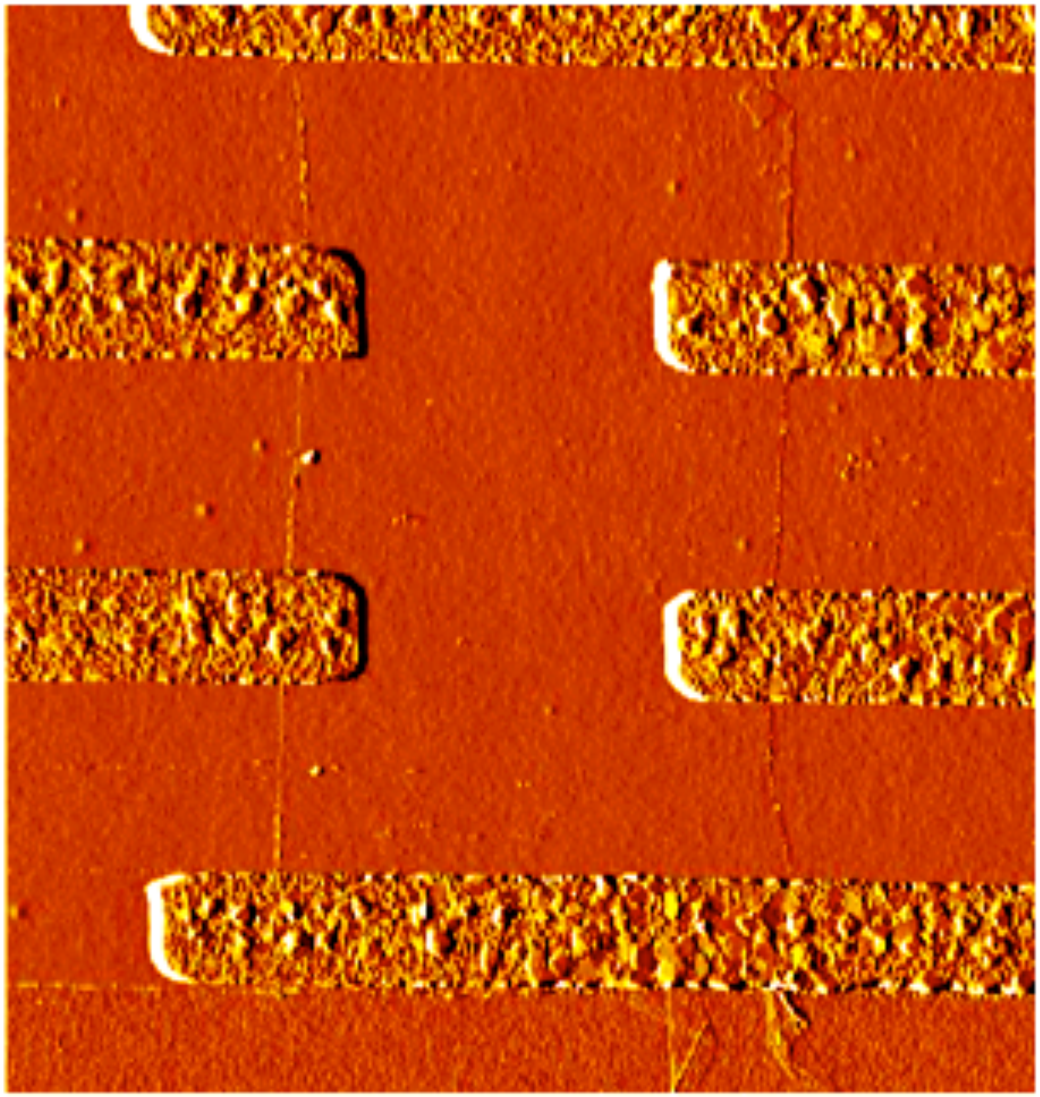


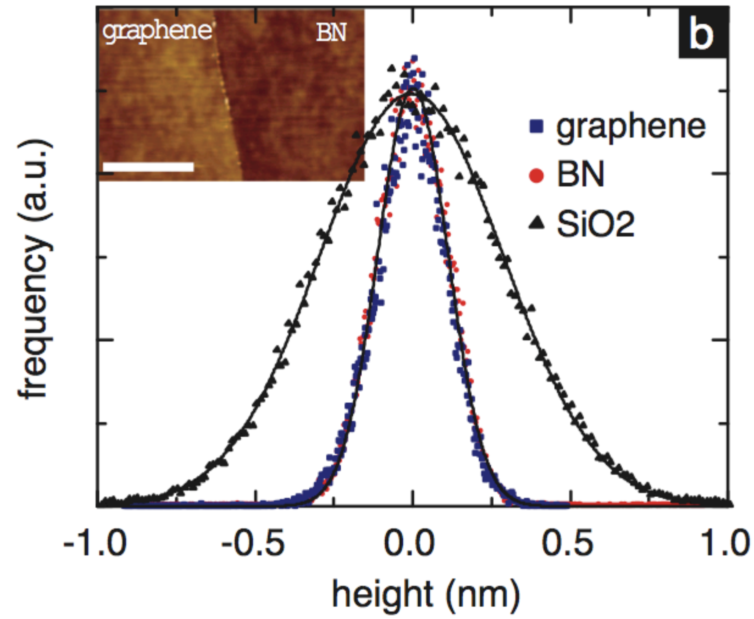
Device fabrication

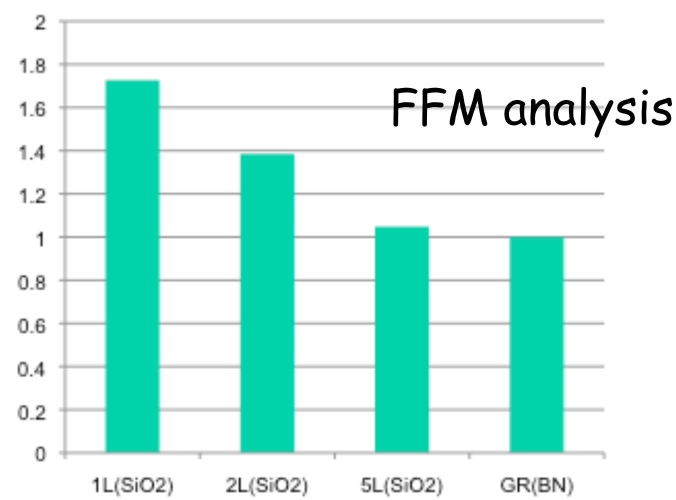
(Anneal in Ar/H_2 after fab)

'Standard' devices: ~10 nm BN on 300 nm SiO_2.

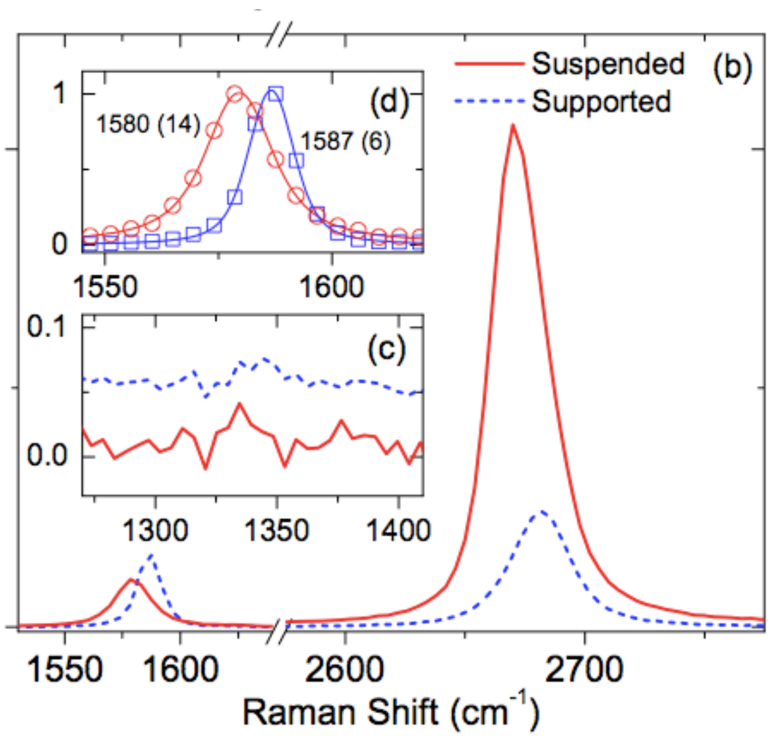
Graphene on BN is very flat, and well-adhered!



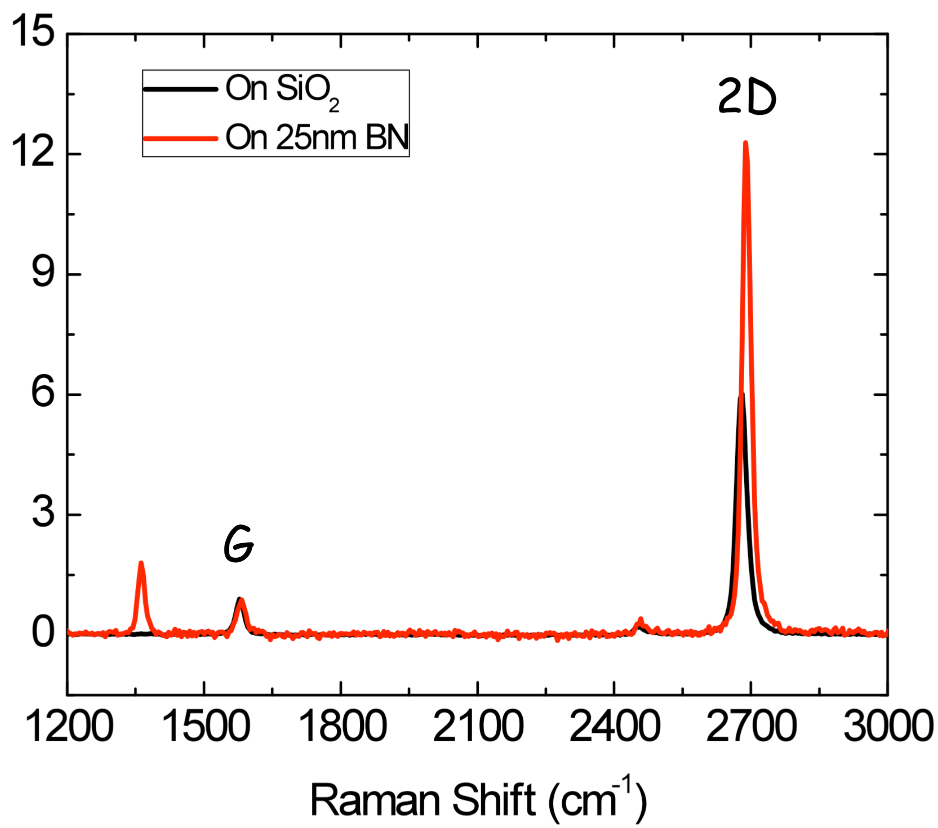




Raman Spectroscopy



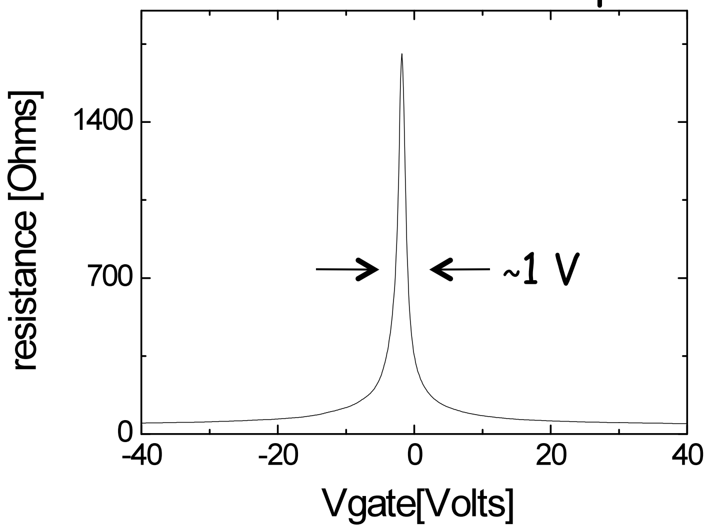
Suspended Graphene
Berciaud et al, Nano Lett 2009



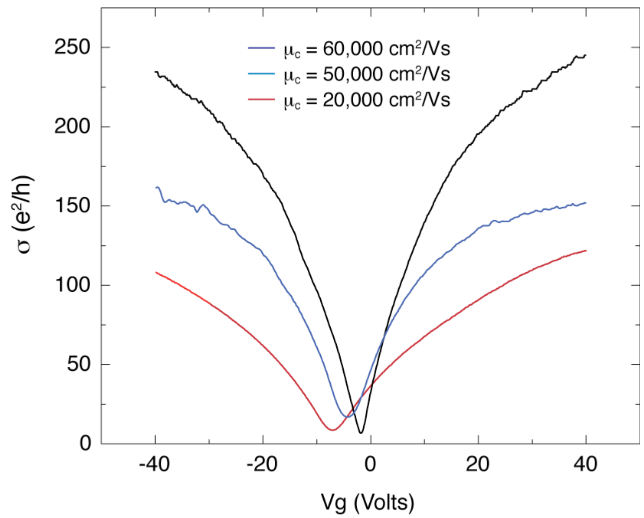
Increase in 2D / G ratio, similar to suspended samples

Low-bias transport

Zero field transport



Comparison between devices



Conductivity

$$\sigma^{-1} = (ne\mu_C + \sigma_o)^{-1} + \rho_s$$

Mobility

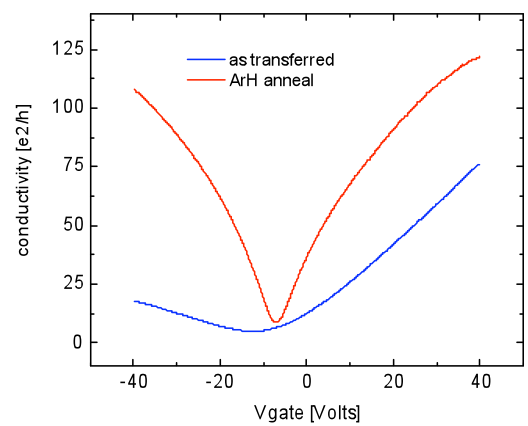
$$\mu_c \sim 60,000 - 100,000 \; cm^2/Vs$$

$$\mu_{FE} \sim 20,000 - 30,000 \; cm^2/Vs$$

Peak width

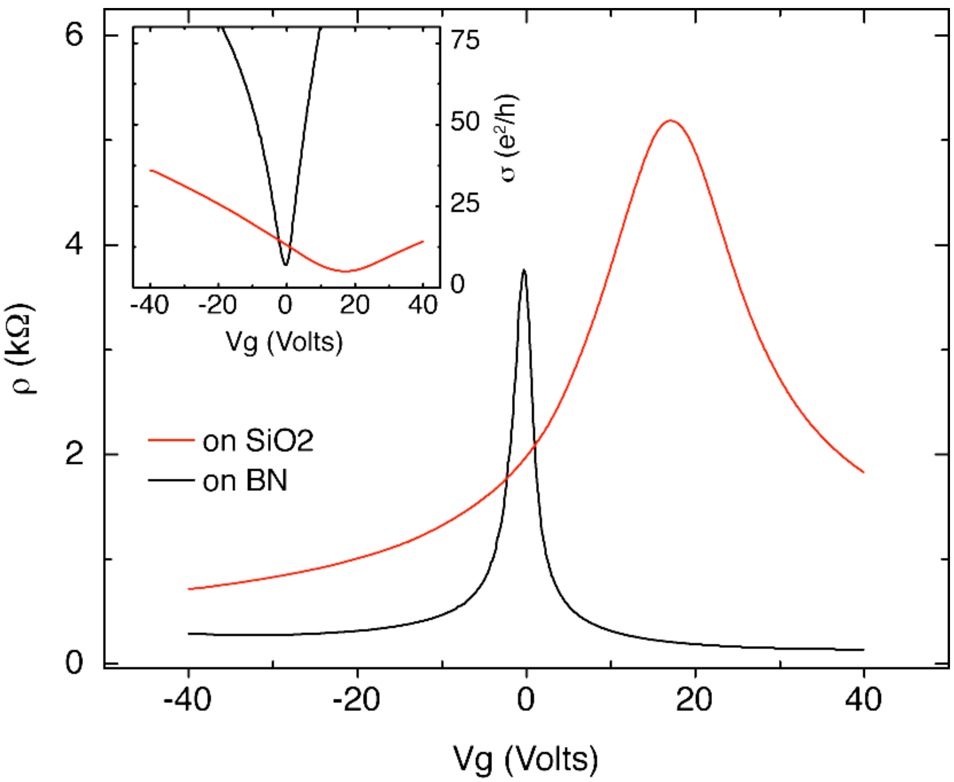
$$\delta\sigma \leq 10^{10} cm^{-2}$$

Effect of annealing

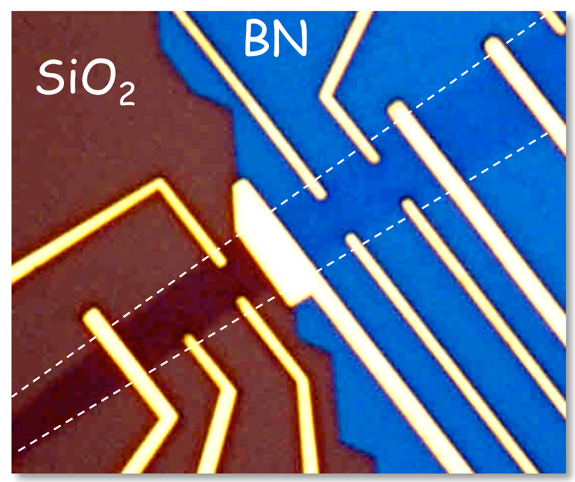


Dean *et al*. Nature Nano. (2010)

Comparison to SiO_2



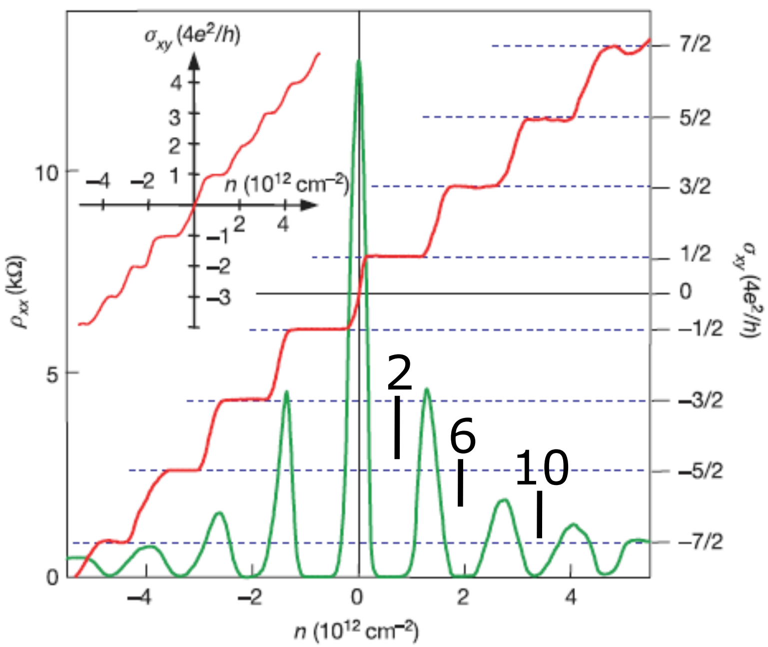
	δn (cm^{-2})	n_{max}
SiO_2	~10^{11}	10^{13}
Suspended	~10^{10}	$1.5x10^{11}$
hBN	$4x10^{10}$	10^{13}



- greatly enhanced mobility on h-BN compared to SiO_2
- CNP peak width reduced by nearly order of magnitude
- virtually no doping even after annealing
- virtually no hysteresis

Integer Quantum Hall Effect

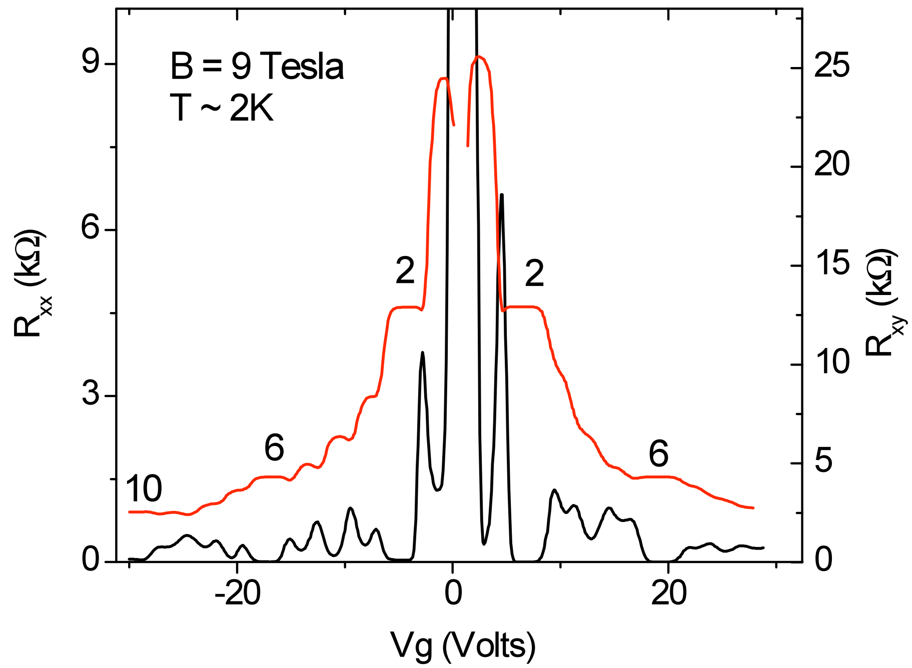
graphene on SiO_2



$$\sigma_{xy} = \frac{4e^2}{h}\left(n + \frac{1}{2}\right)$$

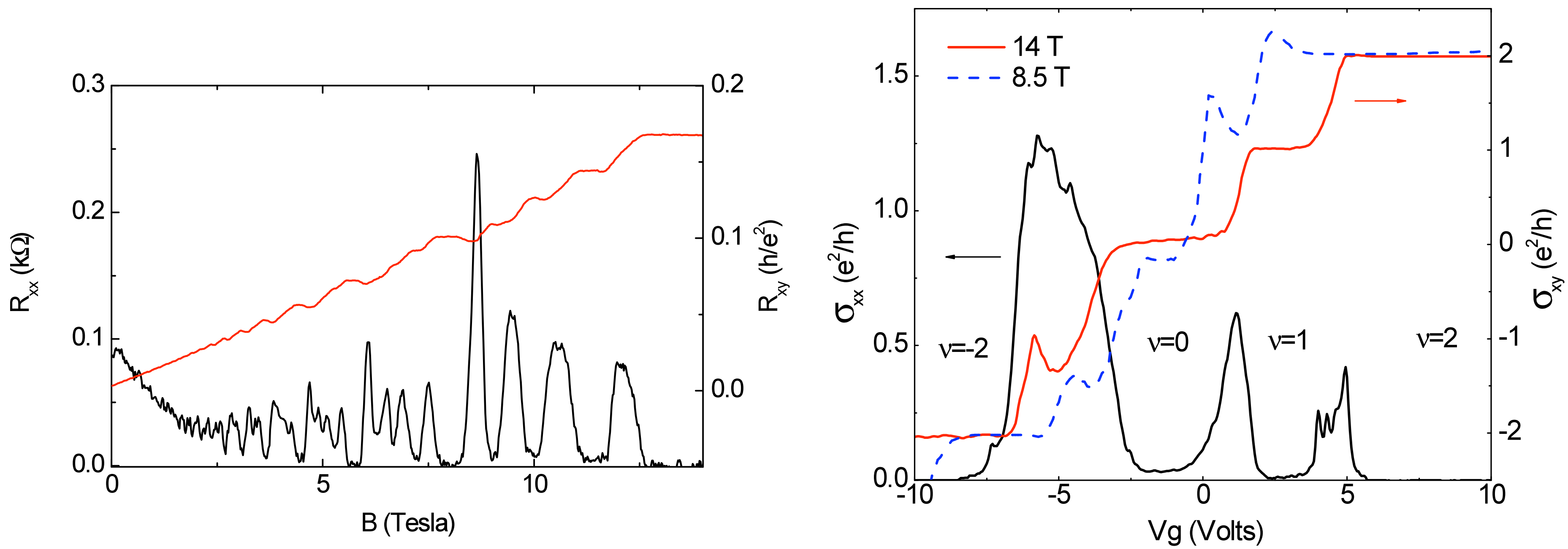
"unconventional" QHE

graphene on BN



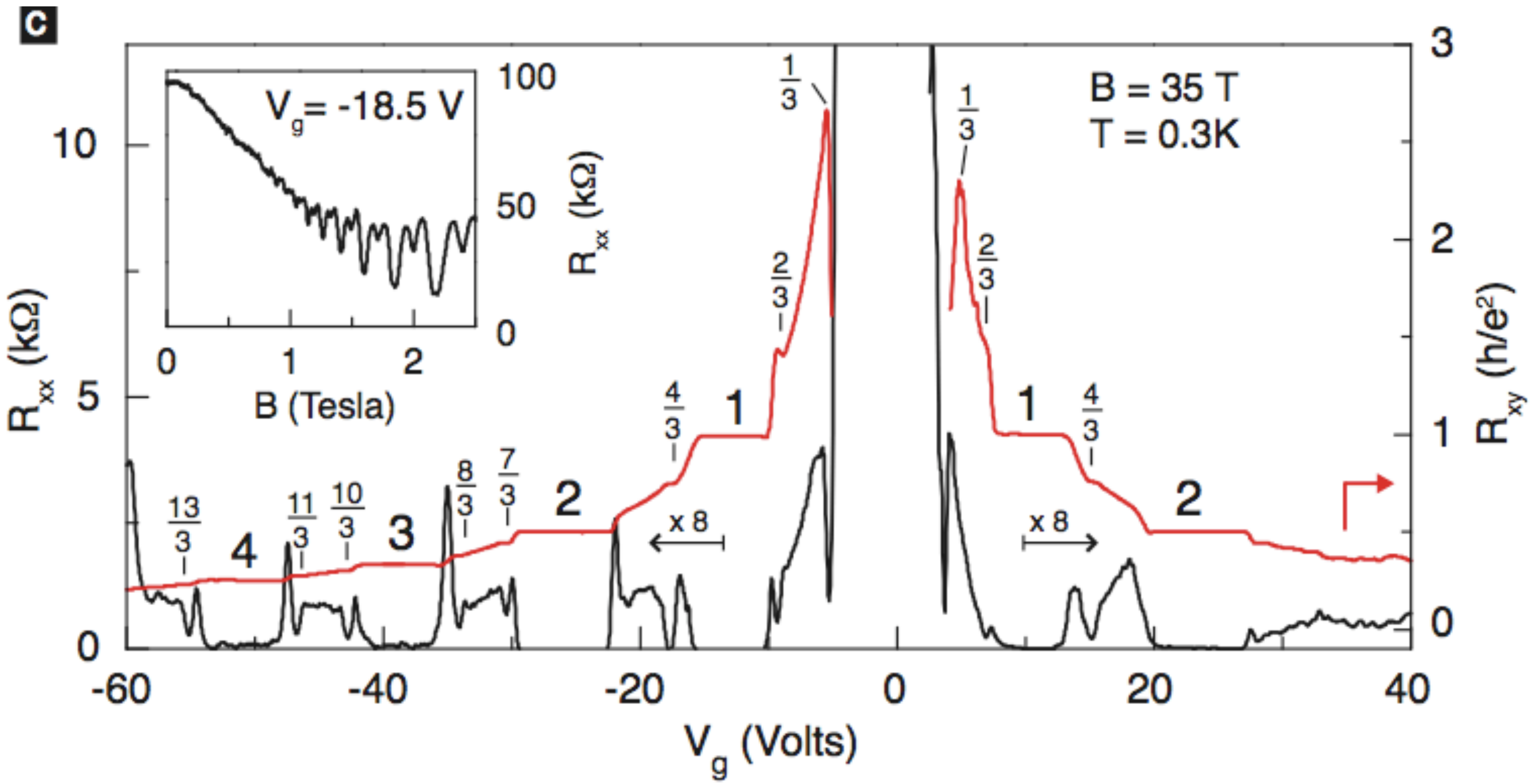
see all integer QHE states!

Integer Quantum Hall Effect



On BN, the degeneracy of the Landau Levels is fully split…

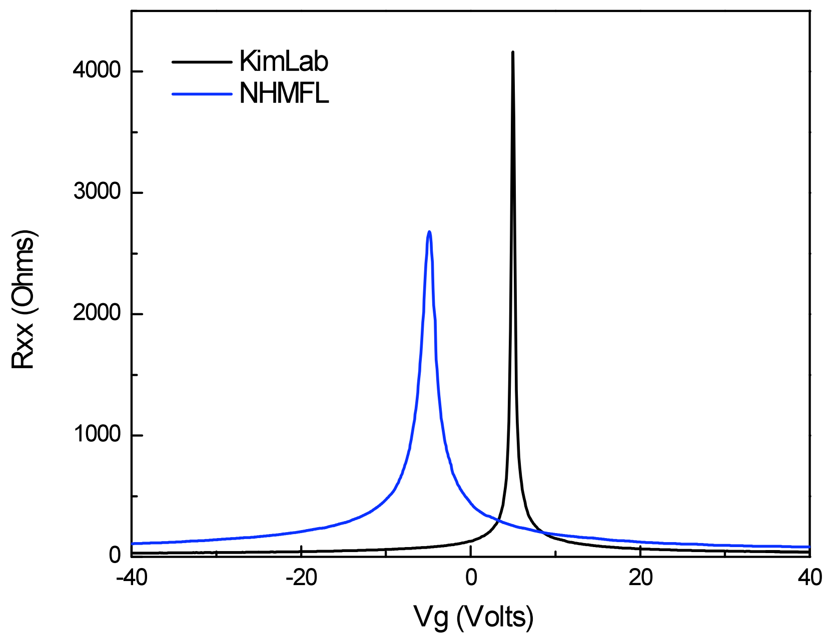
Fractional Quantum Hall

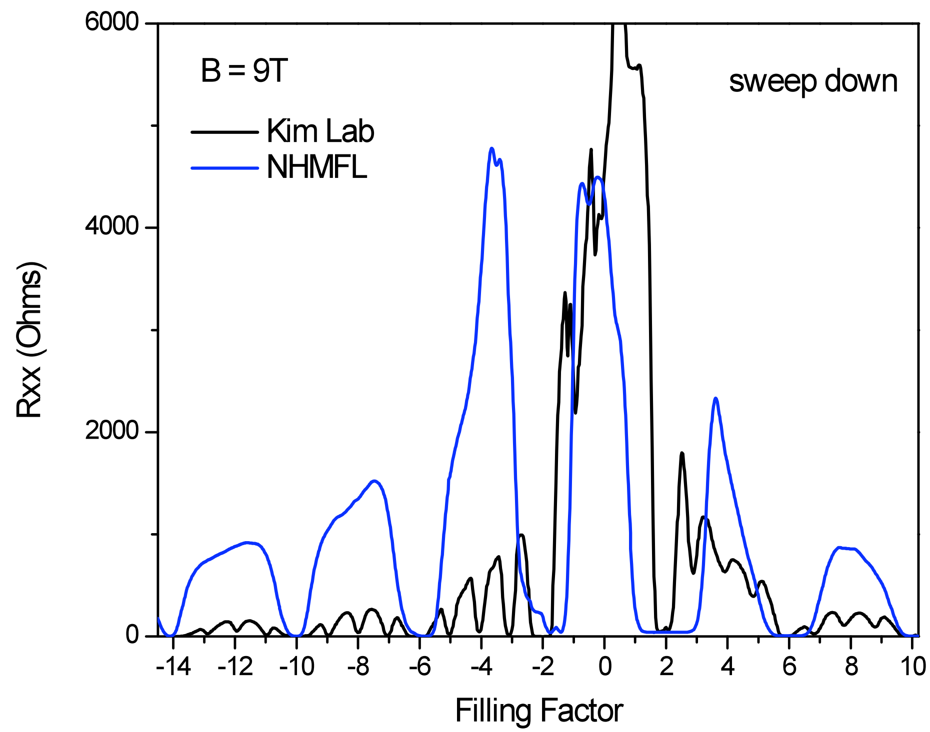


First FQHE on substrate-supported sample, 4-probe measurement
Full set of fractions up to 13/3 (only 1/3 seen previously)

C.R. Dean, et al, Submitted

Disorder from Contamination…



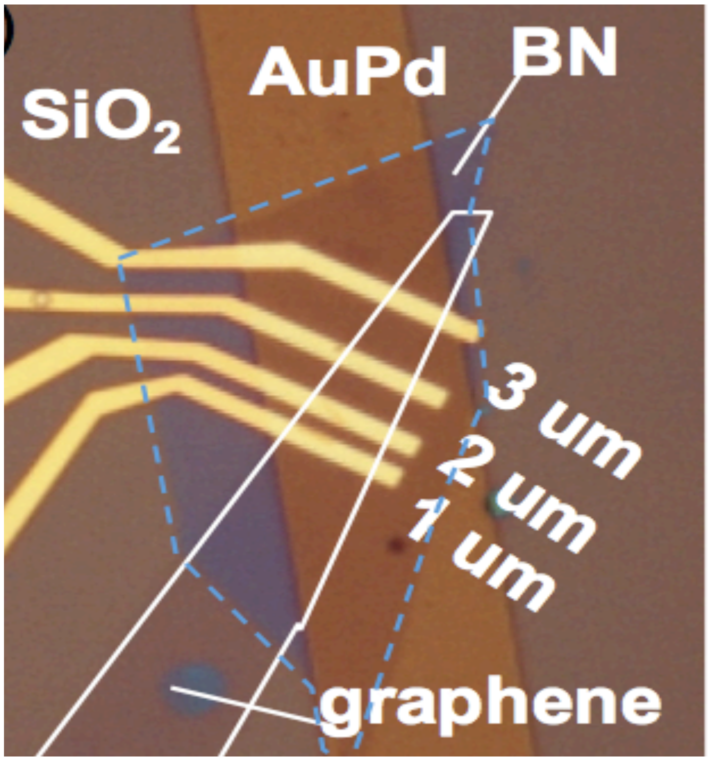


Pump oil contamination causes behavior similar to SiO_2.

- Doping
- Broadening of Dirac peak
- Loss of splitting of IQHE levels

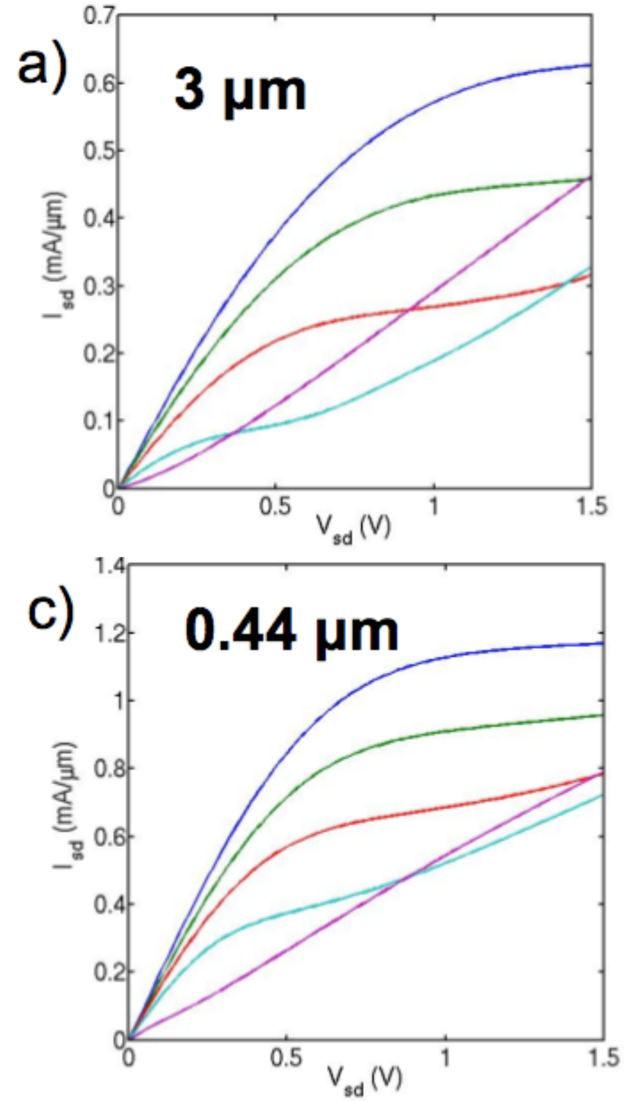
Samples on BN are 'same' as those on SiO_2, just with less disorder…

High-Performance FETs

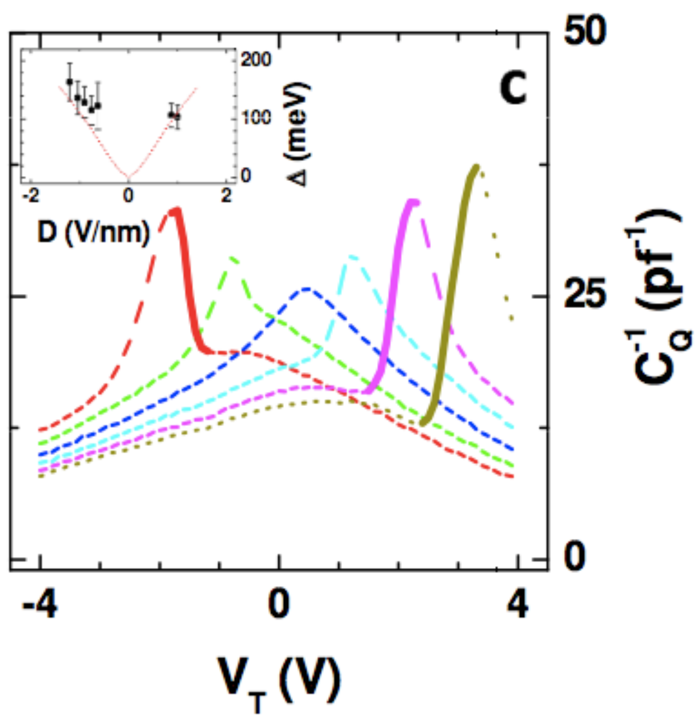


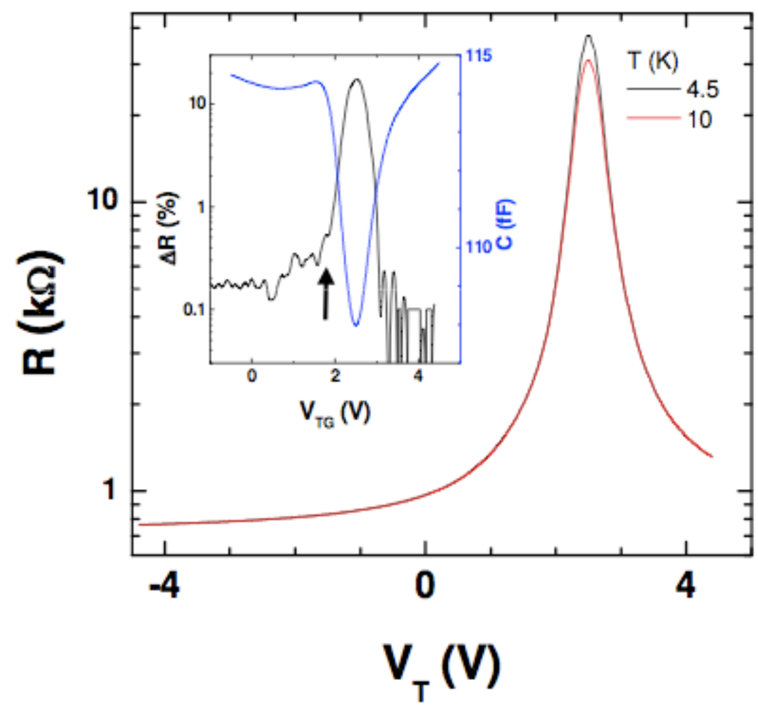
8.5 nm BN back gate

Saturating sub-micron FETs…



Capacitance Measurements: Bilayer Graphene

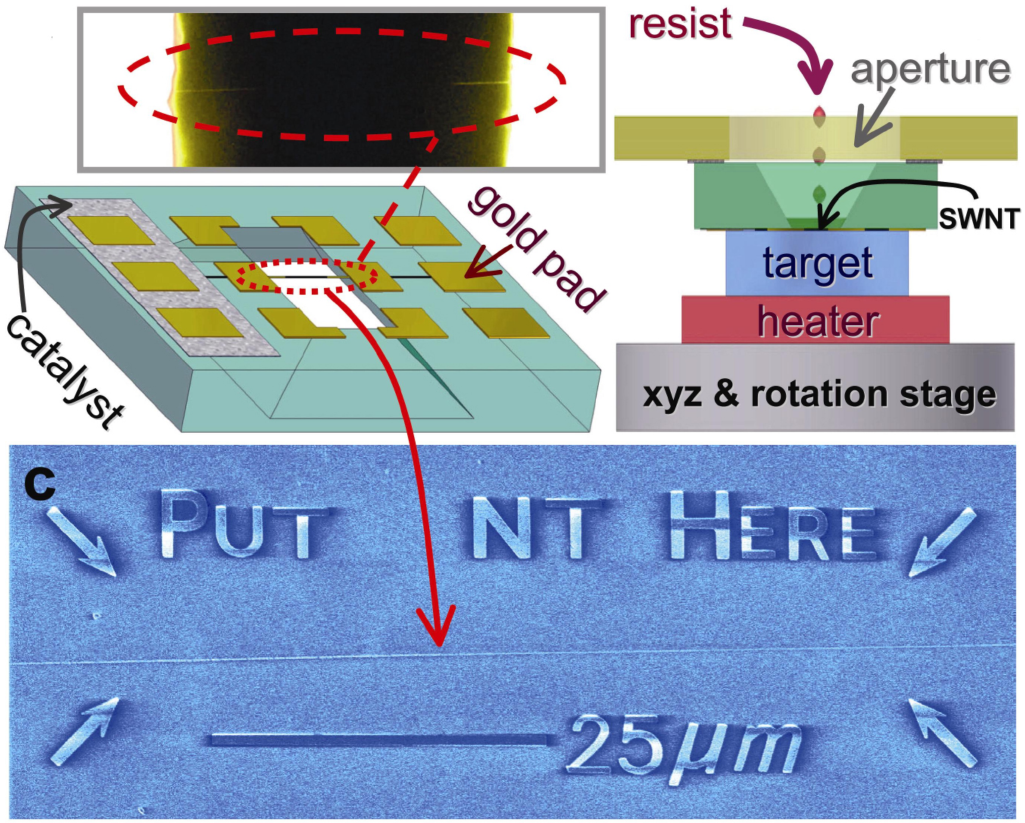




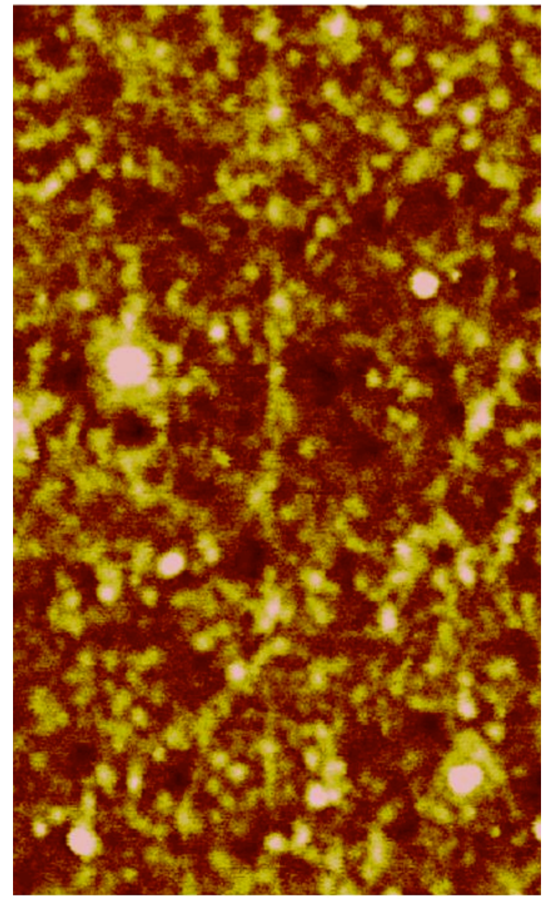
A. Young et al (submitted)

Semiconducting Nanotube on BN

Nanotube transfer technique

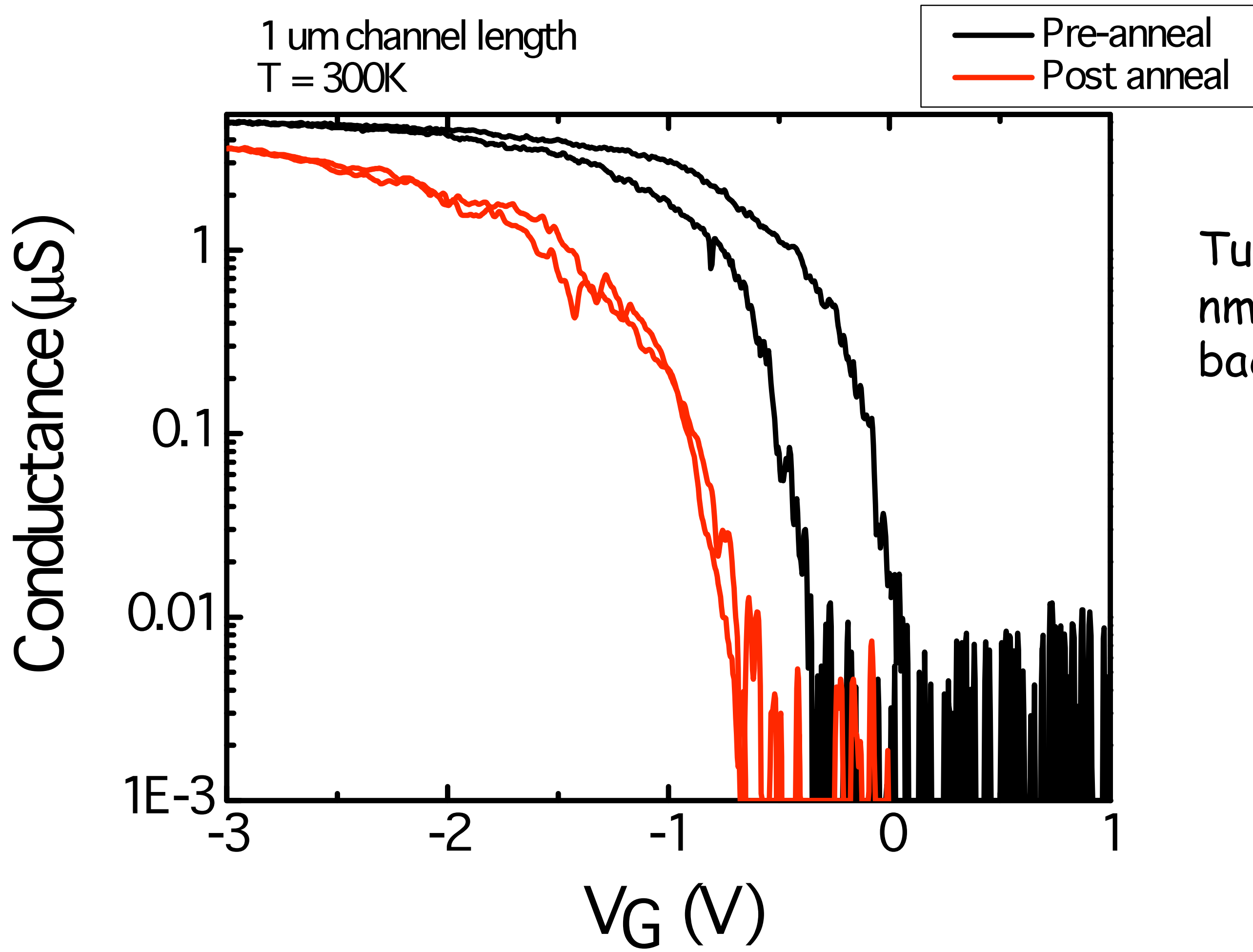


Huang *et al.*, Nano Letters 5, 1515 (2006)



AFM image of NT on BN:
PMMA residue is problem…

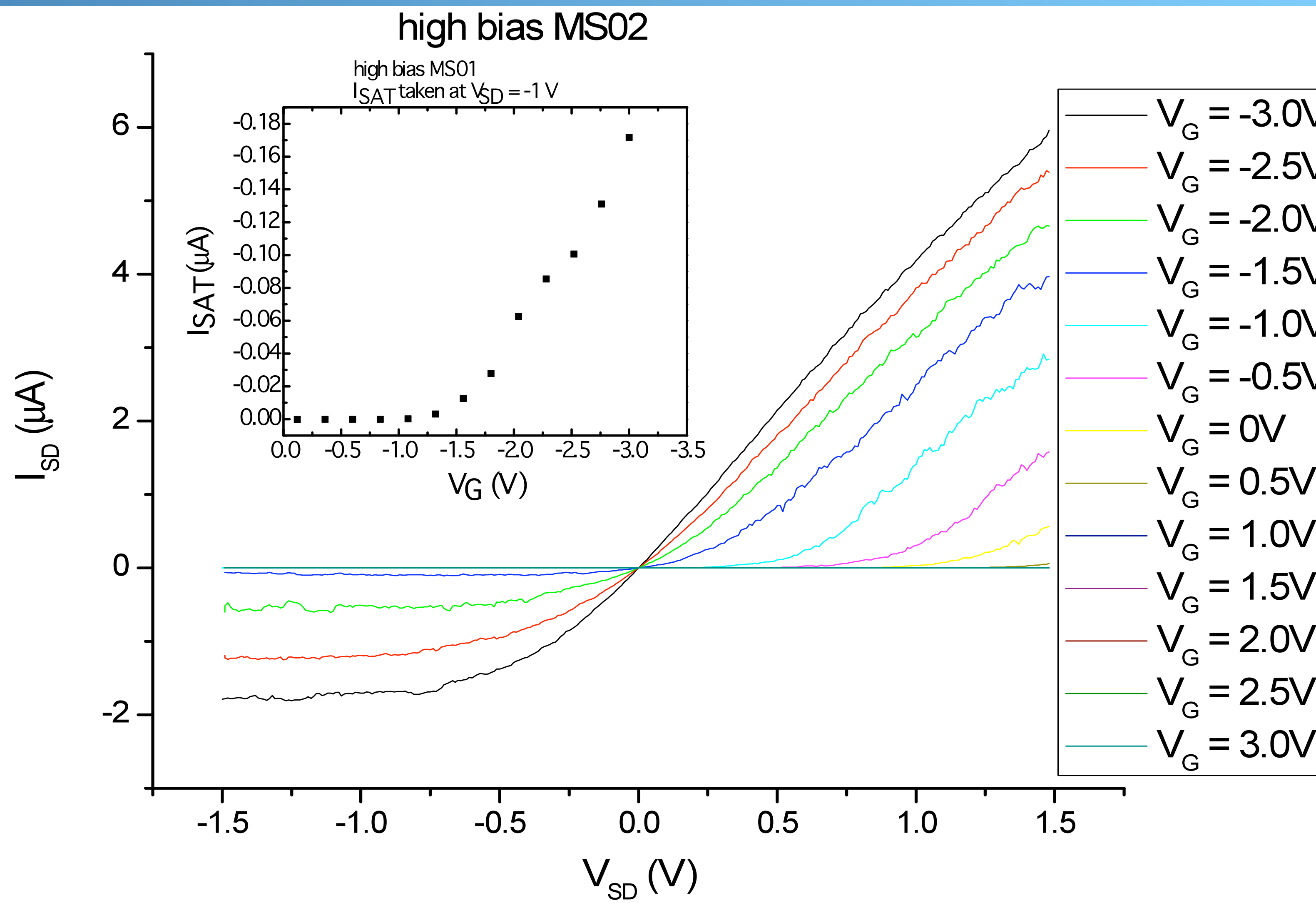
Semiconducting Nanotube on BN



Tube on ~ 4 nm BN, metal back gate.

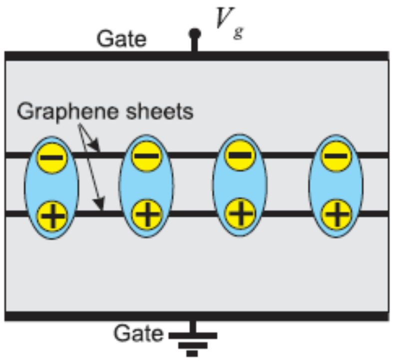
Virtually no hysteresis after annealing in vacuum (450 C)
Subthreshold swing S~170 mV/decade (imperfect contacts)

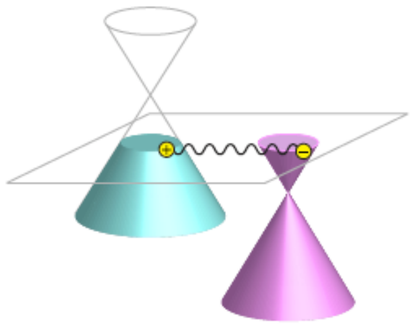
Semiconducting Nanotube on BN



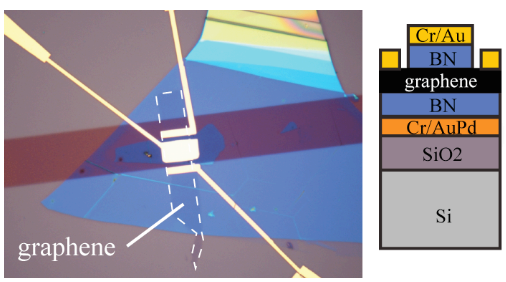
V_{sat} ~ 2 X 10^7 (similar to on SiO_2 see Chen and Fuhrer PRL 2005)

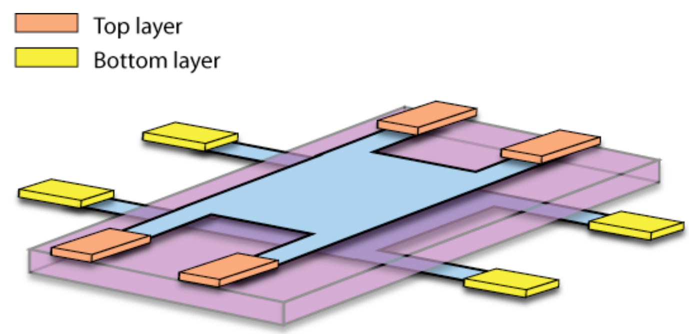
Future: Multilayer Devices e.g. Exciton Condensation





Requirements:
- double layer strucutre with small
  interlayer separation
- independent control of charge
  carrier type and density
- Very low scattering





H Min, R. Bestride, J.-J. Su, and A. H. MacDonald, PRB (2008): T_c ~ 300 K

Kharitinov and Efetov, Semicond. Sci. Technol. (2010): T_c < 1 mK

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