Graphene - from pencil to Nobel prize, passing through QED

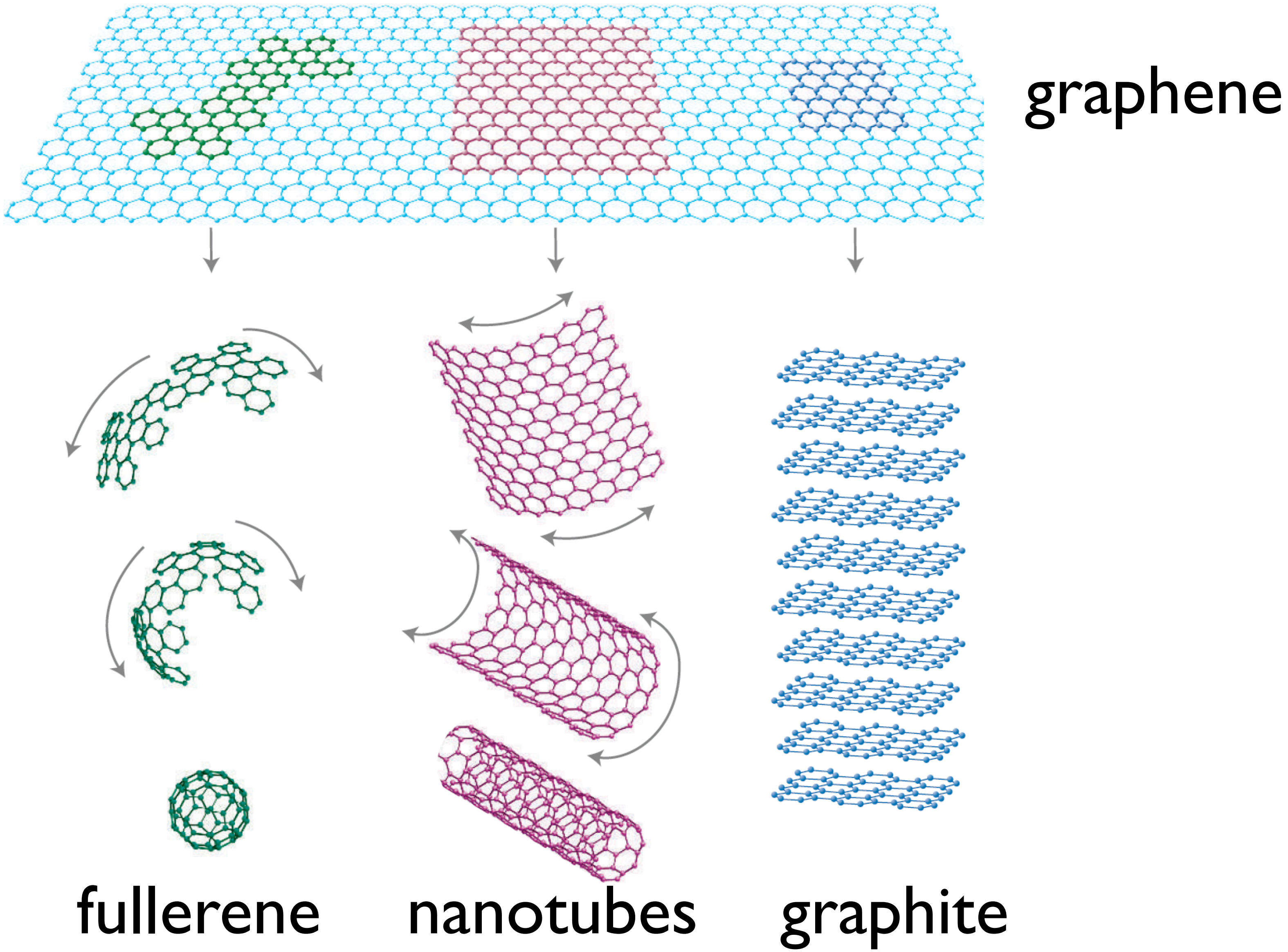
Stefano Borini
Istituto Nazionale di Ricerca Metrologica (INRIM)

Seminario Fisica-Università di Torino - 21/10/10

Andre Geim

Konstantin Novoselov

The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov *"for groundbreaking experiments regarding the two-dimensional material graphene"*



The Nobel Prize in Chemistry 1996 was awarded jointly to Robert F. Curl Jr., Sir Harold W. Kroto and Richard E. Smalley *"for their discovery of fullerenes"*.

Graphene: a well known material, since many years...

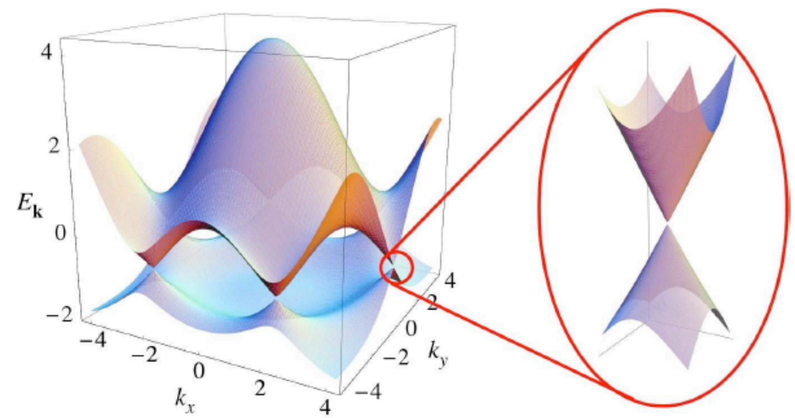
PHYSICAL REVIEW VOLUME 71, NUMBER 9 MAY 1, 1947

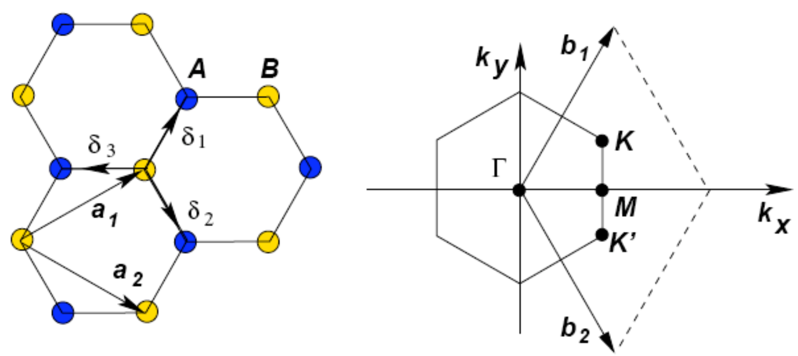
The Band Theory of Graphite

P. R. WALLACE*

2. ZONE STRUCTURE OF A SINGLE HEXAGONAL LAYER

Since the spacing of the lattice planes of graphite is large (3.37A) compared with the hexagonal spacing in the layer (1.42A), a first approximation in the treatment of graphite may be obtained by neglecting the interactions between planes, and supposing that conduction takes place only in layers.

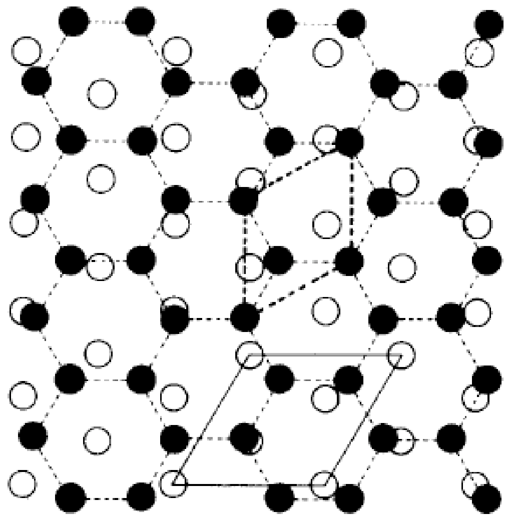




Unique dispersion relations: linear near the Dirac point

→ Massless Dirac fermions

Graphene: a well known material, since many years...



LEED AND AUGER ELECTRON OBSERVATIONS OF THE SiC (0001) SURFACE

A.J. VAN BOMMEL, J.E. CROMBEEN and A. VAN TOOREN
Philips Research Laboratories, Eindhoven, The Netherlands

Received 12 August 1974; revised manuscript received 21 October 1974

LEED and AES experiments of the SiC {0001} crystal surfaces show that on heat-treatment these surfaces are easily "covered" with a layer of graphite by evaporation of silicon. The graphite layer, which has a distinct crystallographic relation to the SiC crystal, is monocrystalline on the Si-face and mostly polycrystalline on the C-face. A speculation about the mechanism of the initial graphitization of the basal faces of SiC is given.

Electronic structure of the (2×2)C *p* 4g carbidic phase on Ni{100}

C. F. McConville and D. P. Woodruff
Physics Department, University of Warwick, Coventry CV4 7AL, England, United Kingdom

S. D. Kevan*
AT&T Bell Laboratories, Murray Hill, New Jersey 07974-2070

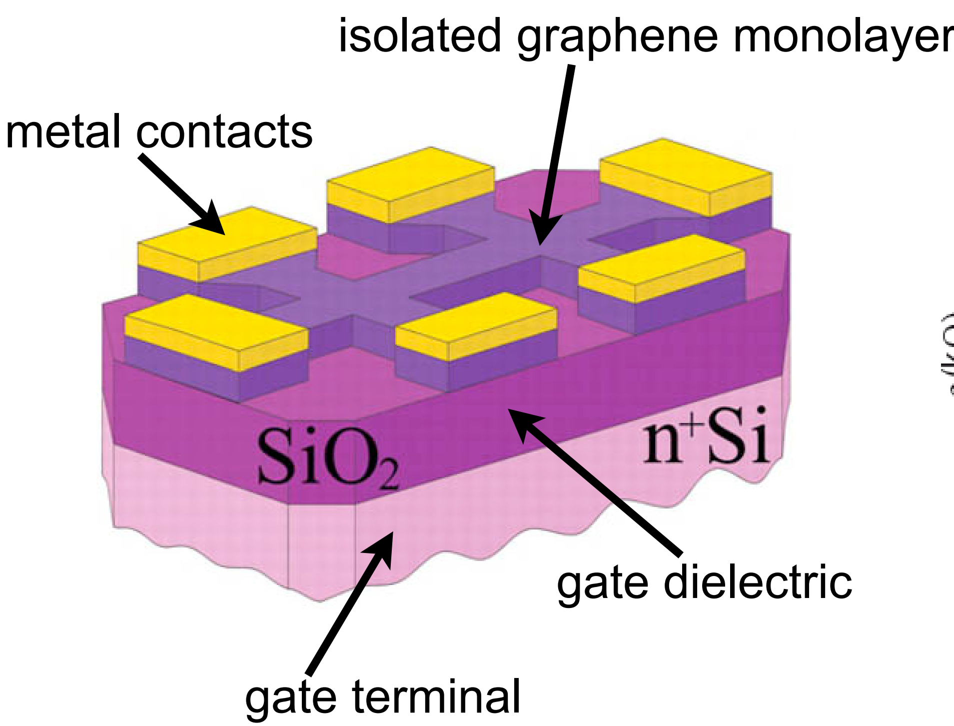
M. Weinert and J. W. Davenport
Physics Department, Brookhaven National Laboratory, Upton, New York, 11973-5000
(Received 24 February 1986)

They found the key for the direct access to the physics of this 2D system

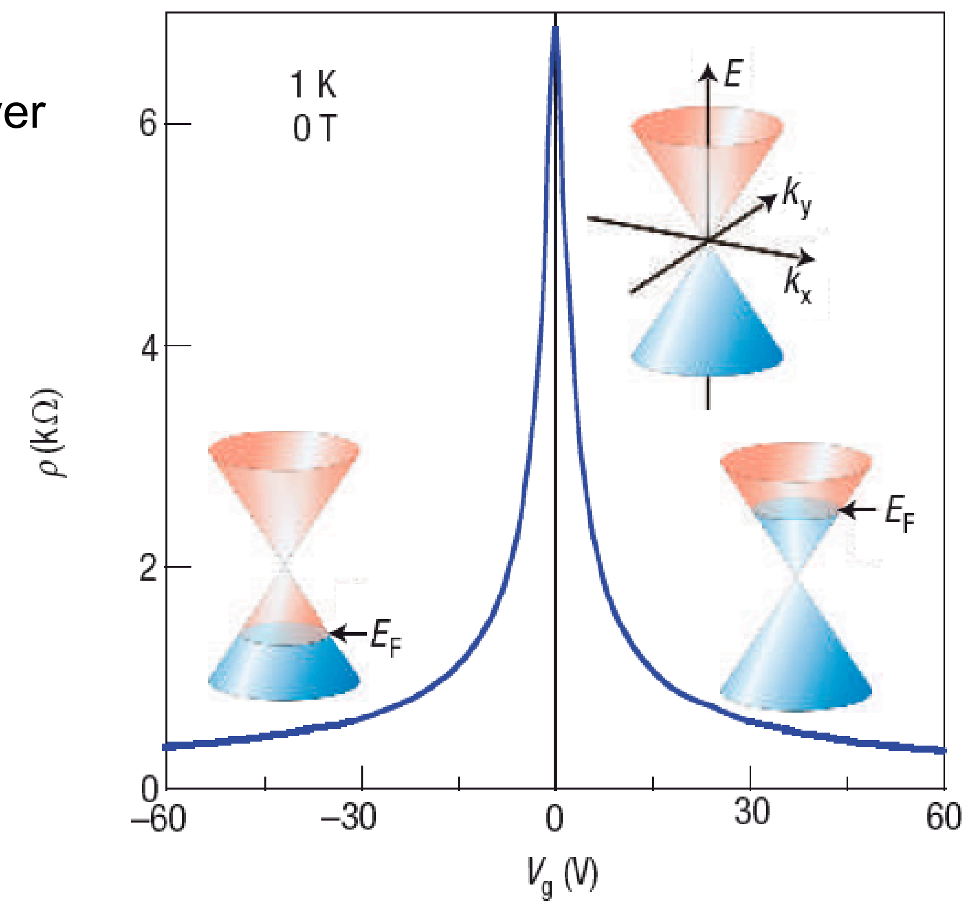
QED in a pencil trace...

[© Geim & Novoselov]

FET devices: Electronic properties



Ambipolar field effect

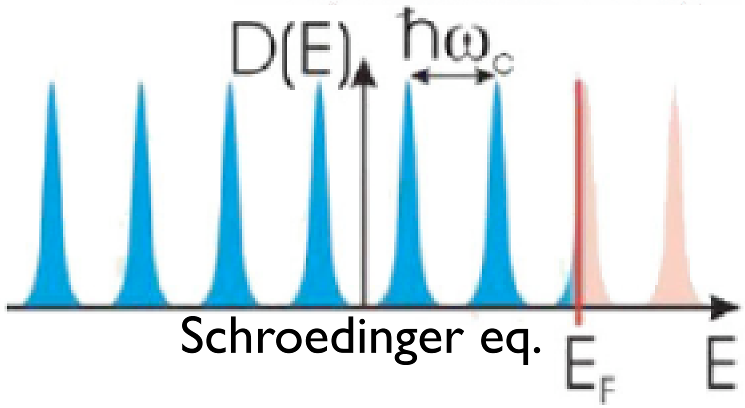


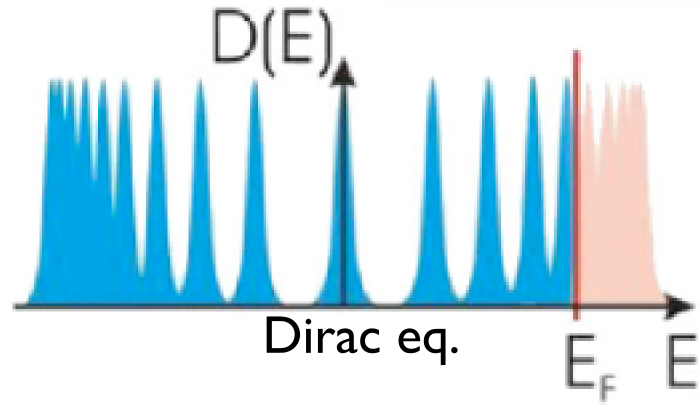
Electric Field Effect in Atomically Thin Carbon Films
K. S. Novoselov, *et al.*
Science **306**, 666 (2004);

Anomalous half-integer QHE: Dirac equation holds

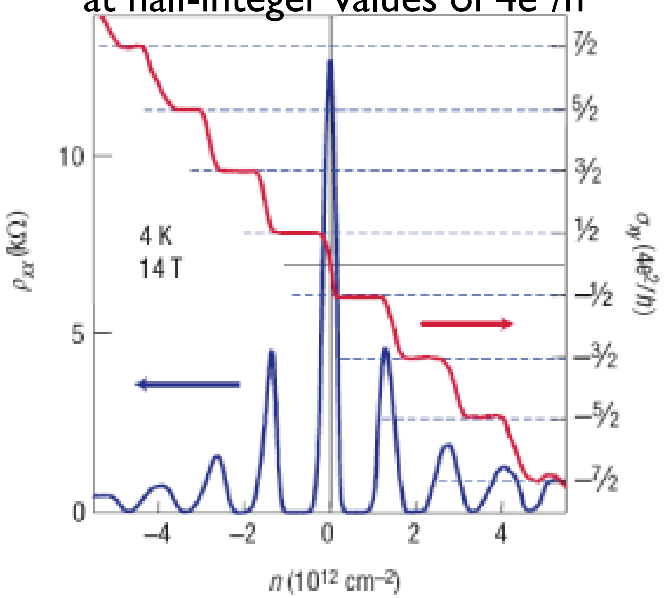
Landau levels:

Normal electrons: $E_{LL} = \pm\hbar\omega_c(N + ½)$ Dirac fermions: $E_{LL} = \pm v_F\sqrt{2e\hbar B}\sqrt{N}$



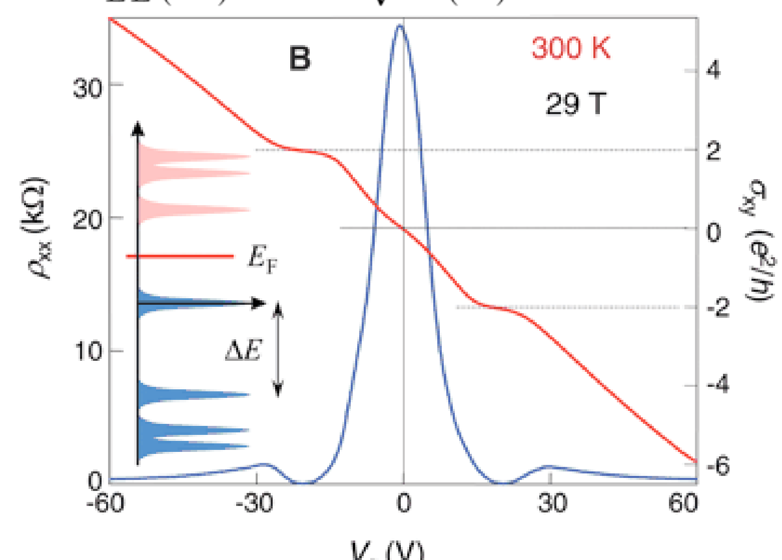


Hall conductivity quantized at half-integer values of $4e^2/h$



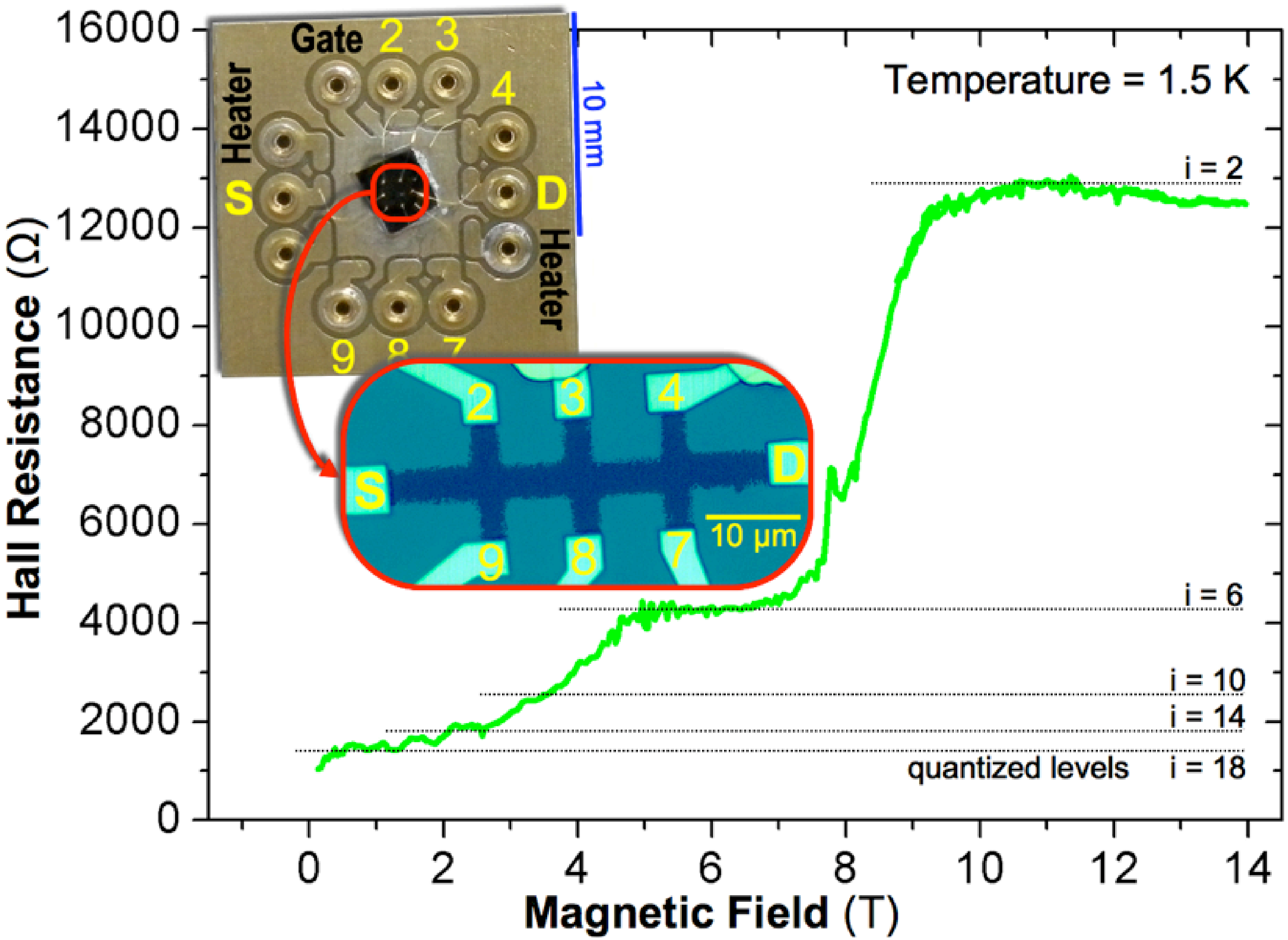
K.S. Novoselov et al, Nature 438, 197 (2005)
Y. Zhang et al., Nature 438, 201 (2005)

$\Delta E_{LL}(K) = 420\sqrt{B(T)}$: QHE at RT

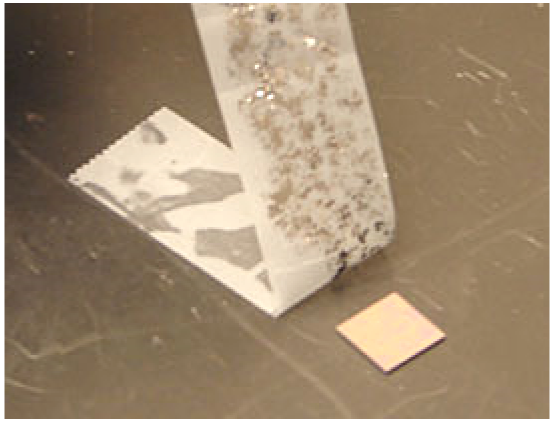


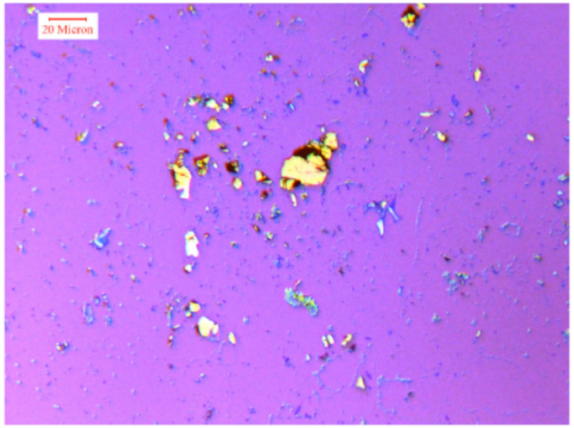
K.S. Novoselov et al, Science 315, 1379 (2007)

QHE graphene devices at INRIM

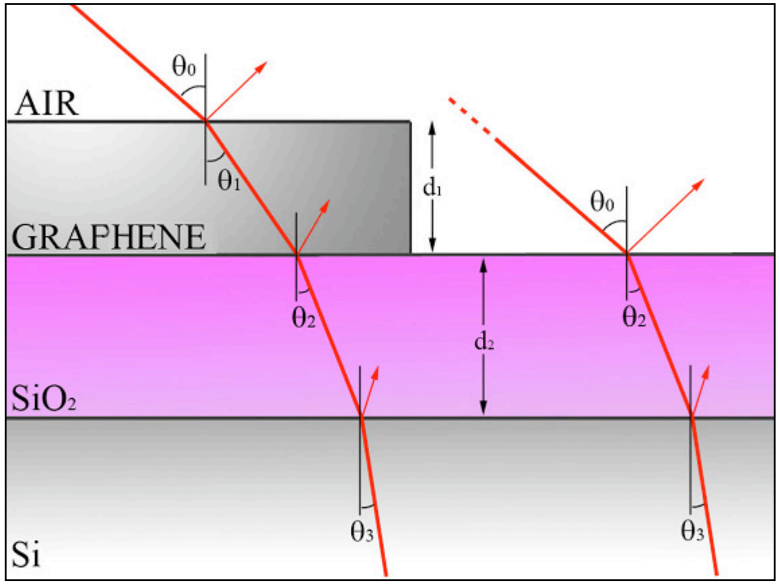


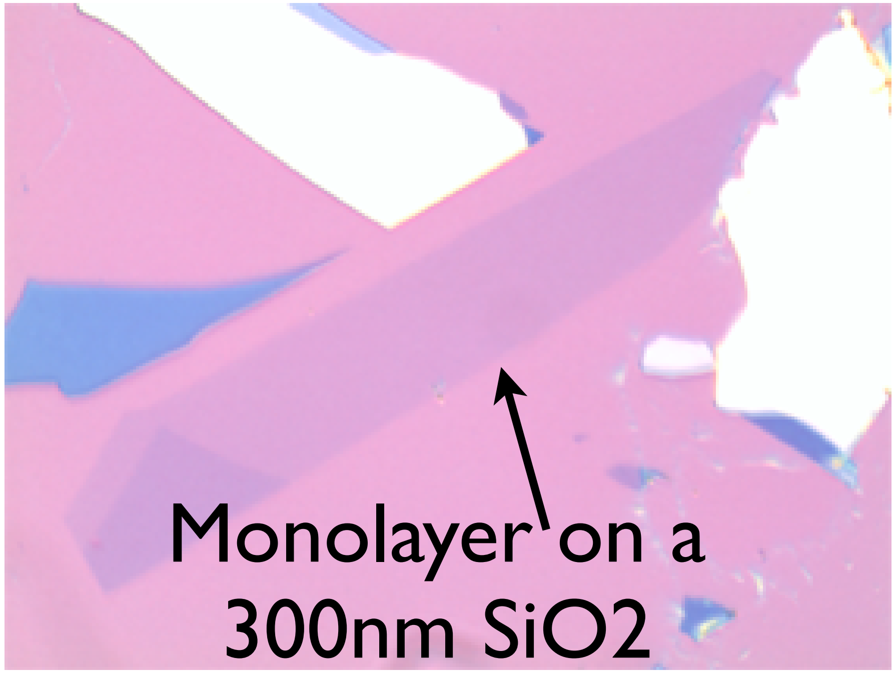
Optical properties





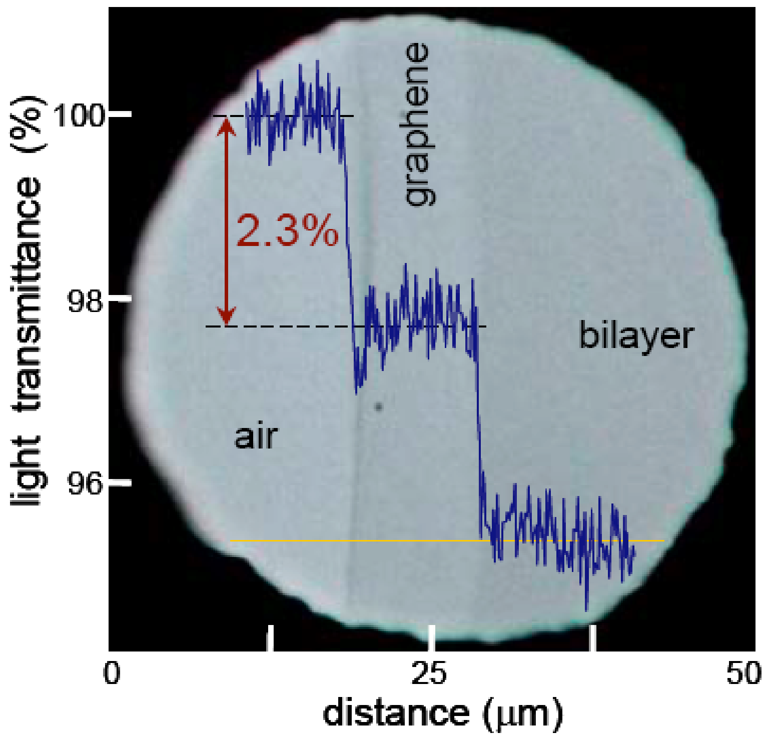
monolayers are there, somewhere...



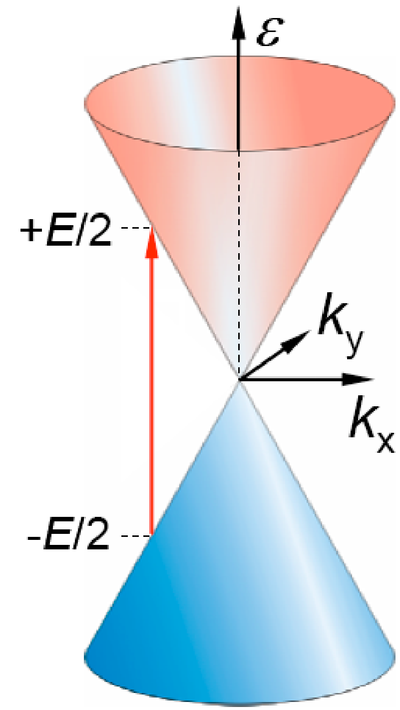


P. Blake et al., "Making graphene visible", APL 91, 063124 (2007)

Quantized opacity



R.R. Nair et al., Science 320, 1308 (2008)



$$\text{absorption } P = W_a/W_i = \pi e^2/\hbar c = \pi\alpha,$$

Interaction of light with relativistic particles described by a coupling constant: fine structure constant

Optical constants from contrast analysis and quantized opacity

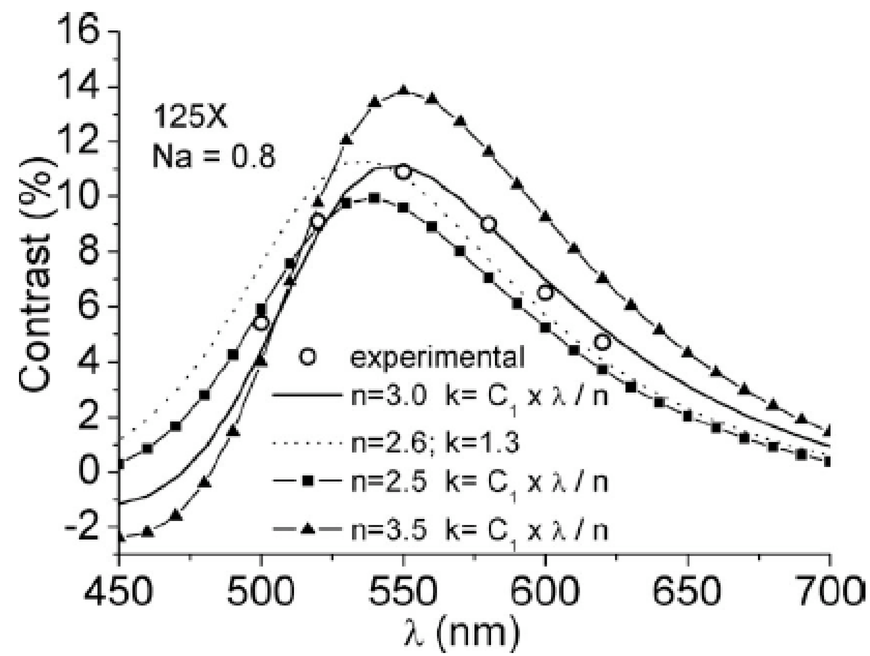
APPLIED PHYSICS LETTERS 94, 031901 (2009)

Optical constants of graphene layers in the visible range

M. Bruna and S. Borini[a)]
Electromagnetic Division, INRIM, Strada delle Cacce 91, Torino I-10135, Italy

$$k = -\frac{\lambda}{4\pi n d_1}\ln(1-\pi\alpha) \equiv C_1\frac{\lambda}{n}$$

$$n = 3.0; \quad k = \frac{C_1}{3}\lambda$$

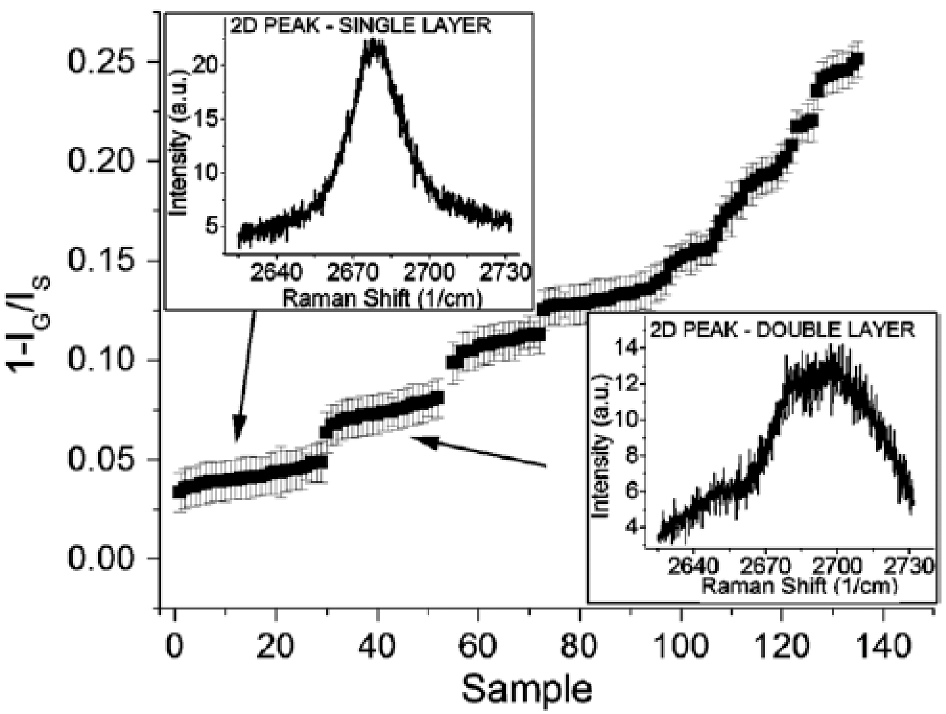


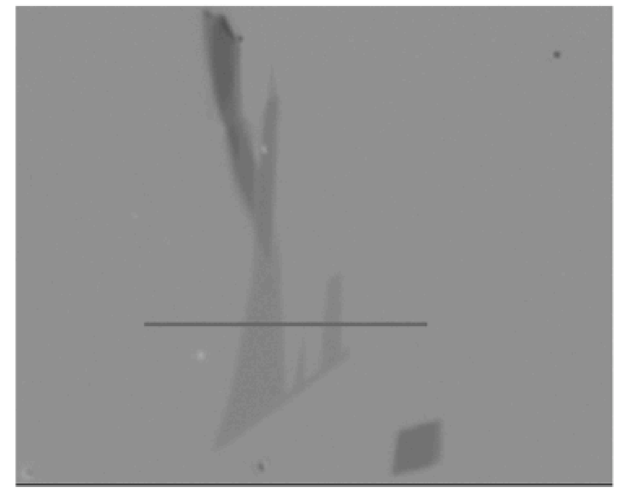
Optical contrast: easy high-throughput analysis of graphene layers

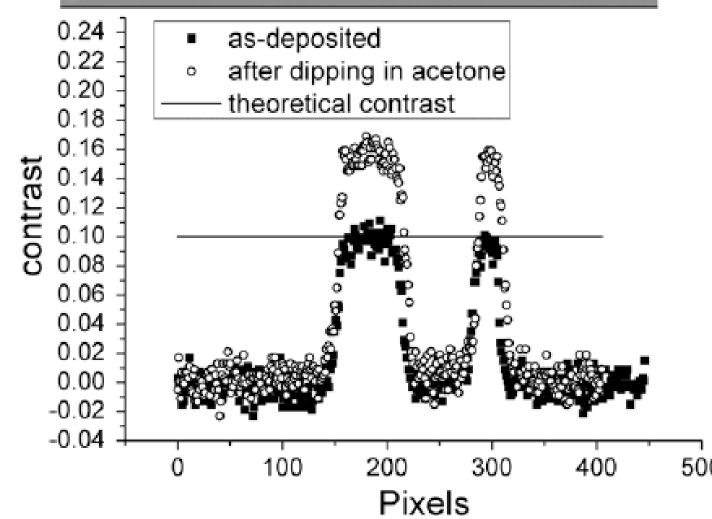
IOP PUBLISHING JOURNAL OF PHYSICS D: APPLIED PHYSICS
J. Phys. D: Appl. Phys. 42 (2009) 175307 (5pp) doi:10.1088/0022-3727/42/17/175307

Assessment of graphene quality by quantitative optical contrast analysis

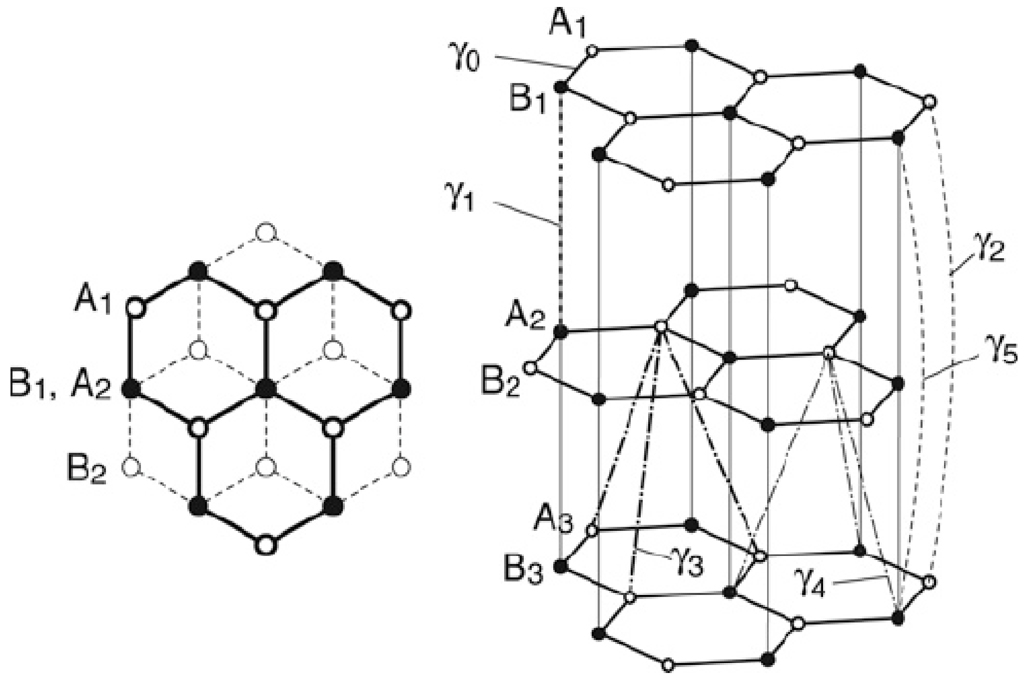
Matteo Bruna and Stefano Borini



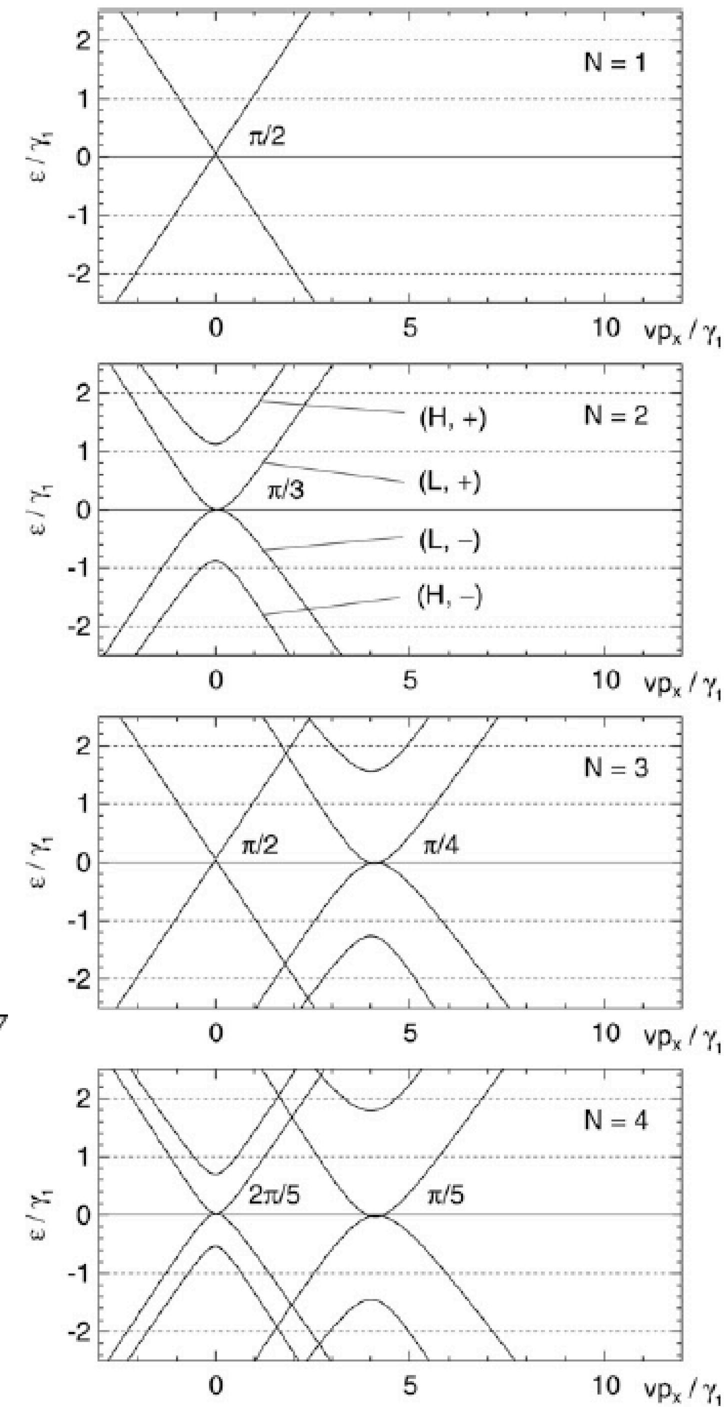




Evolution of electronic bands with stacking graphene layers



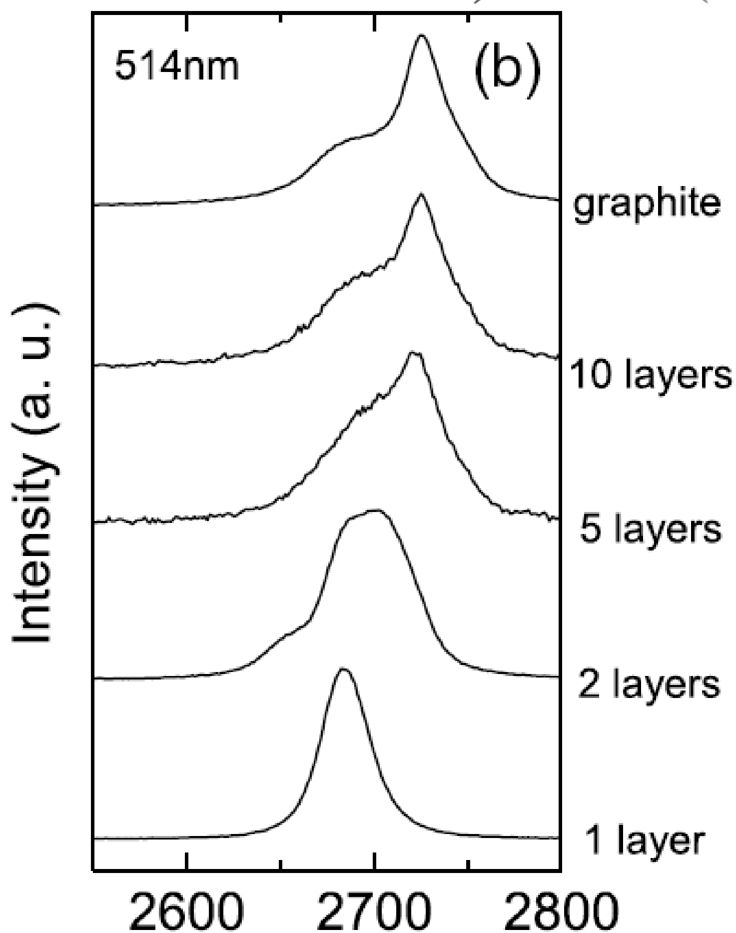
M. Koshino, T. Ando / Solid State Communications 149 (2009) 1123–1127

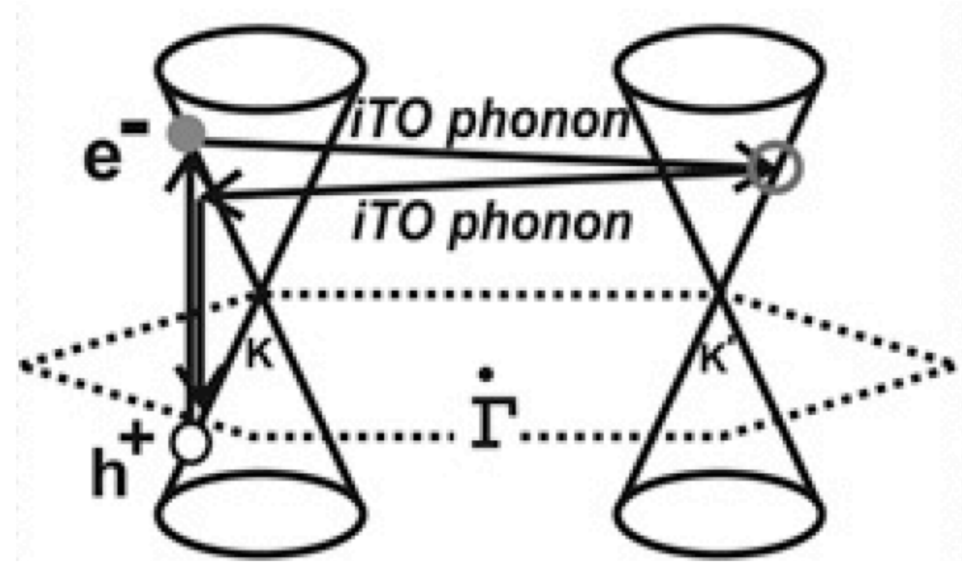


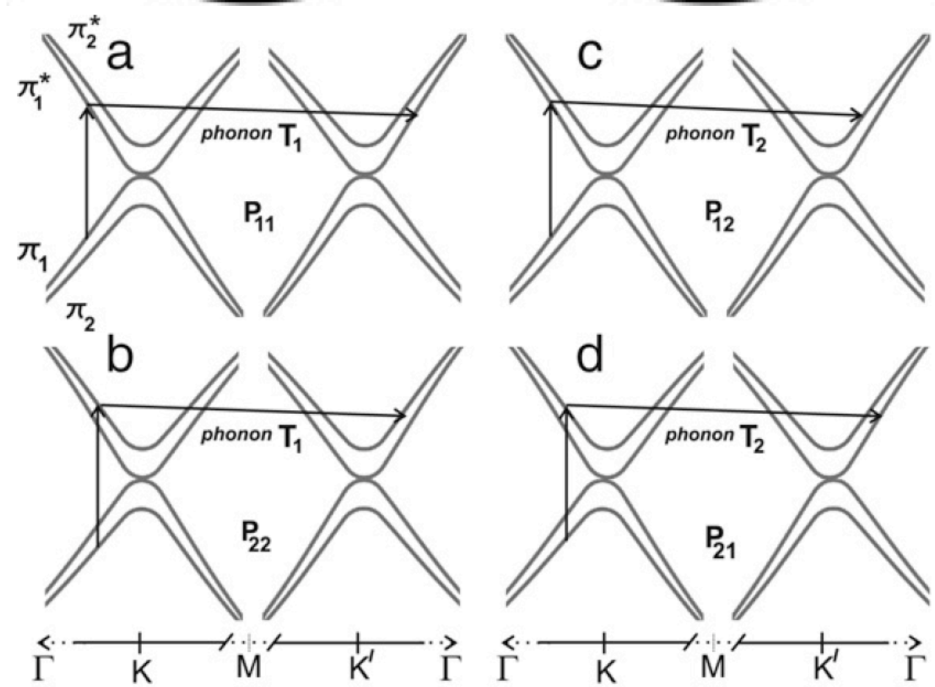
Vibrational spectroscopy
can monitor such evolution

Raman spectrum of graphene

A.C. Ferrari et al., PRL **97,** 187401 (2006)





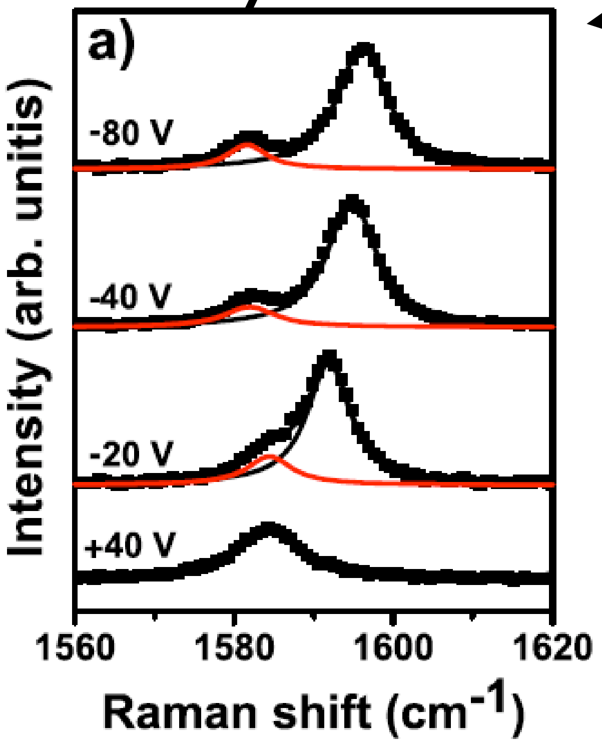


L.M. Malard et al. / Physics Reports 473 (2009) 51–87

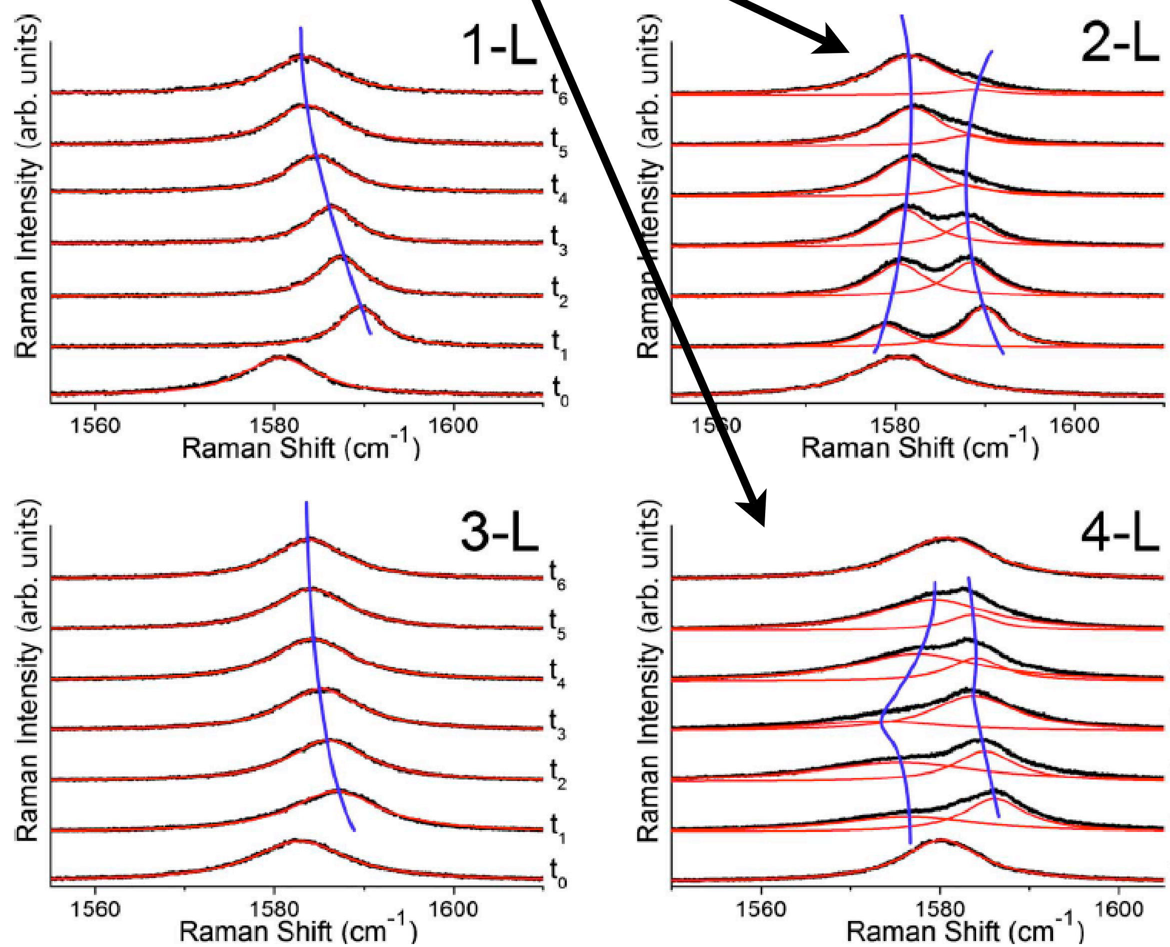
Raman of graphene stacks: symmetry is important

inversion symmetry breaking → G band splitting

bilayer



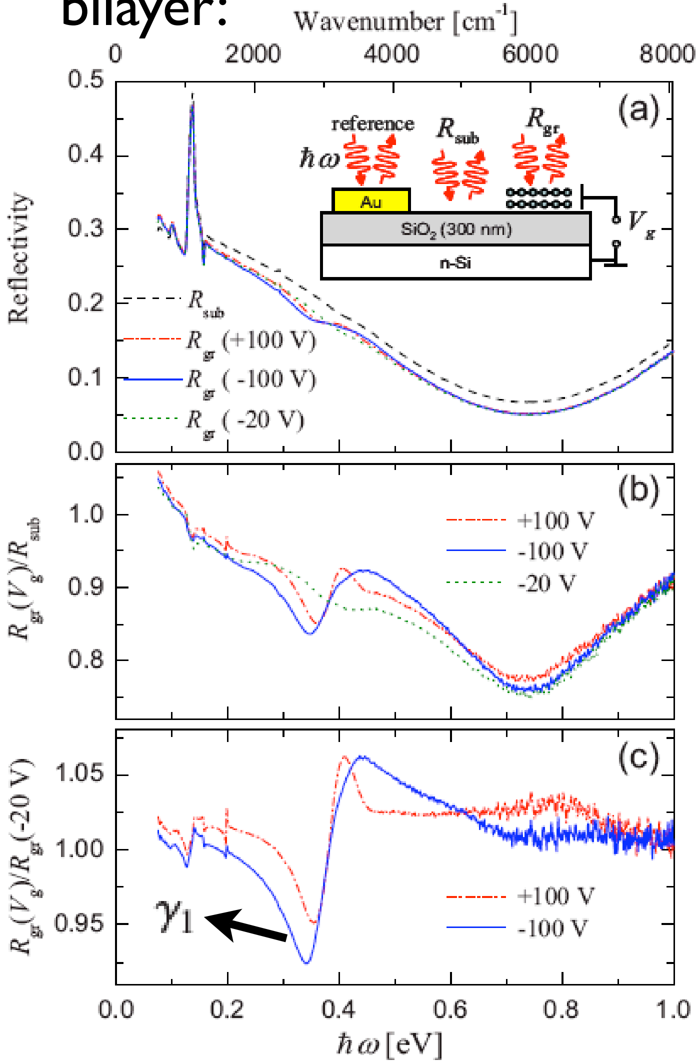
L. Malard et al, PRL 101, 257401 (2008)



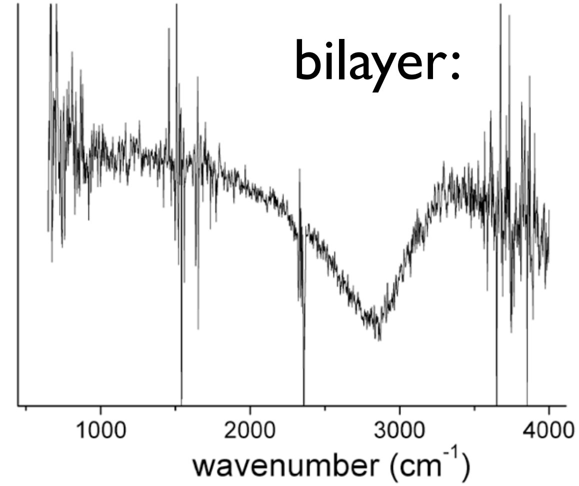
M. Bruna and S. Borini, PRB 81, 125421 (2010)

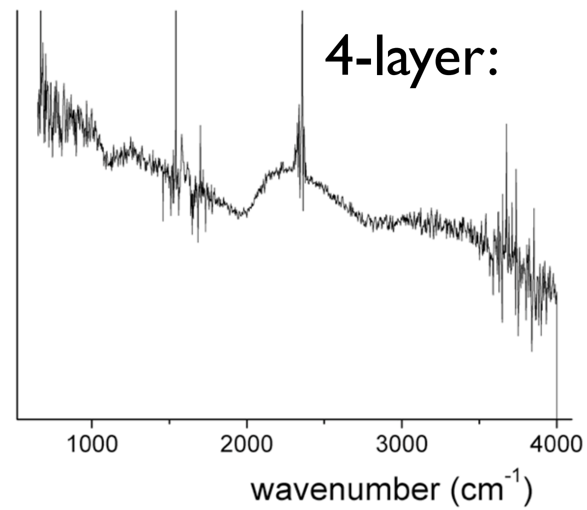
IR spectroscopy

bilayer:



Kuzmenko et al., PRB 80, 165406 (2009)





spectra from INRIM micro-FTIR

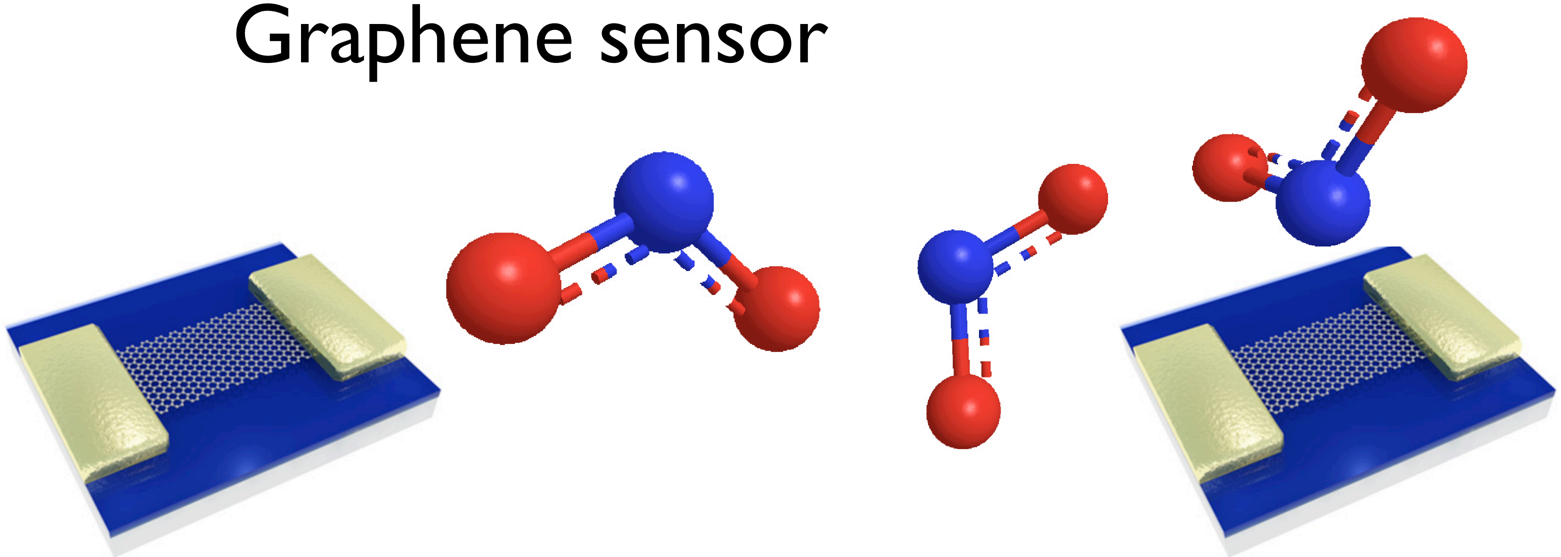
Graphene: an “all-surface” material:

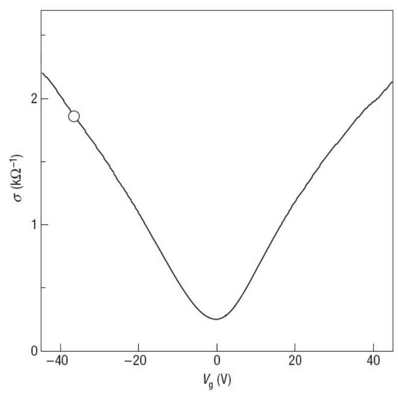
- sensing

- strain engineering / “origami”

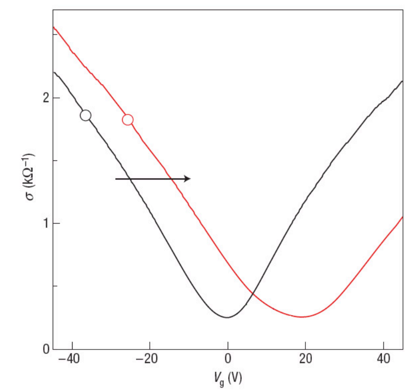
- surface functionalization dramatically changes the material (graphane, fluorographene, graphene oxide)

Graphene sensor





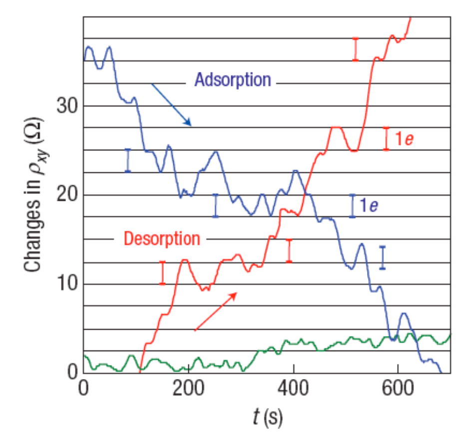
Adsorption of electron-withdrawing molecules



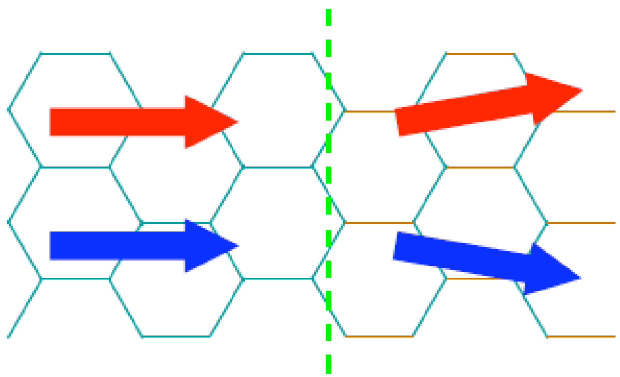
Nature Materials **6**, 652 (2007)

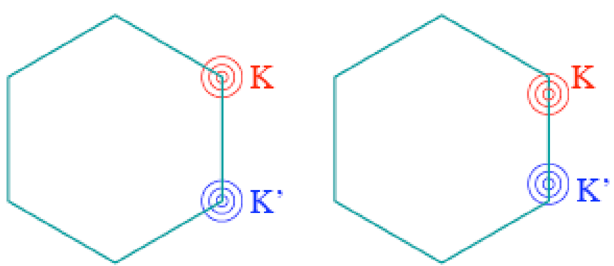
Detection of individual gas molecules adsorbed on graphene

F. SCHEDIN[1], A. K. GEIM[1], S. V. MOROZOV[2], E. W. HILL[1], P. BLAKE[1], M. I. KATSNELSON[3] AND K. S. NOVOSELOV[1]*



Graphene "origami" : Strain engineering

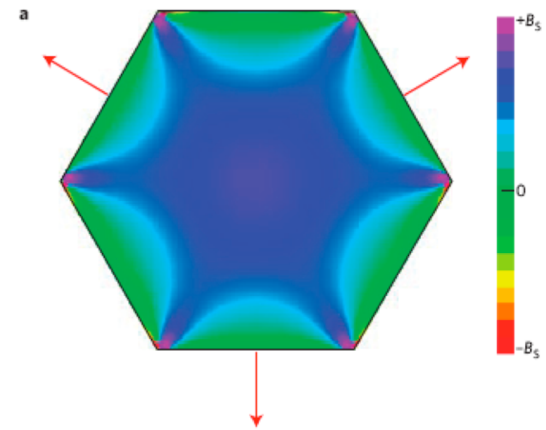


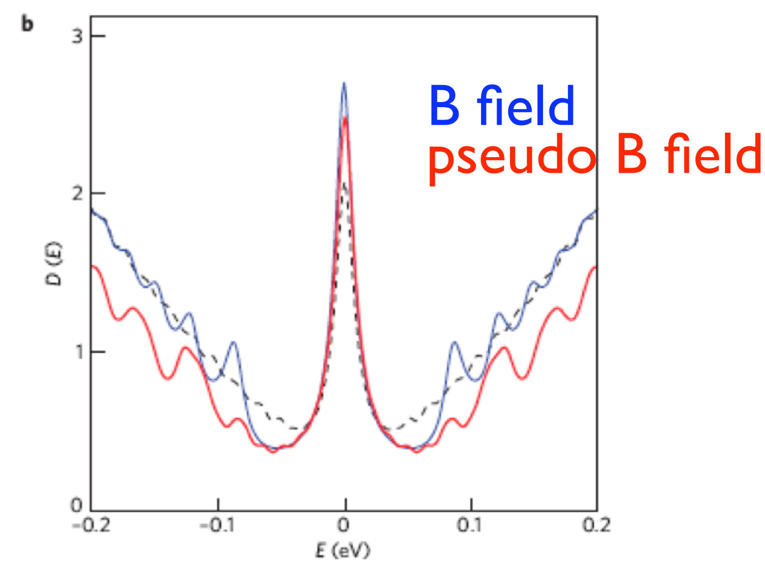


V.M. Pereira and A.H. Castro Neto,
PRL 103, 046801 (2009)

A.H. Castro Neto et al.,
Rev. Mod. Phys. 81, 109 (2009)

Stretching graphene along (100) axes:





Theoretically predicted pseudo-Landau levels

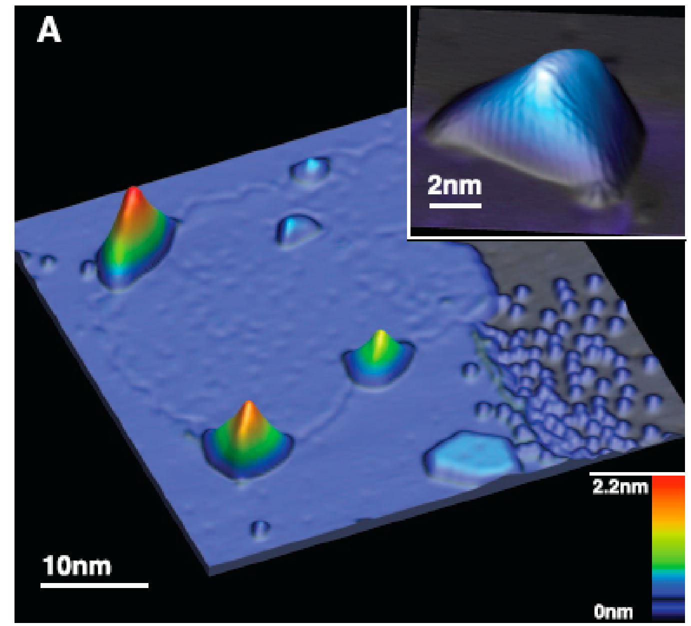
F. Guinea et al., Nature Physics 6, 30 (2010)

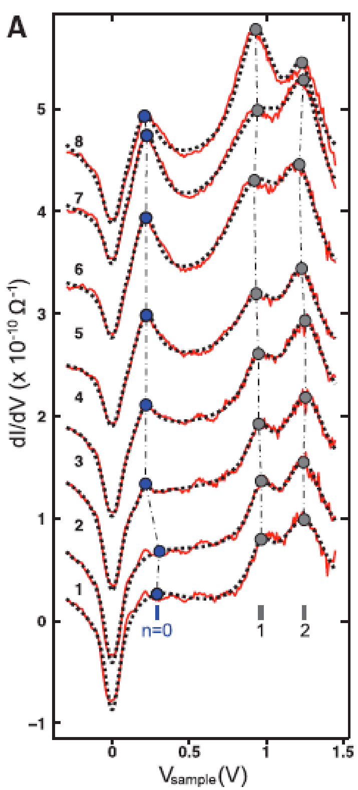
Strain engineering: pseudo magnetic field experimentally observed

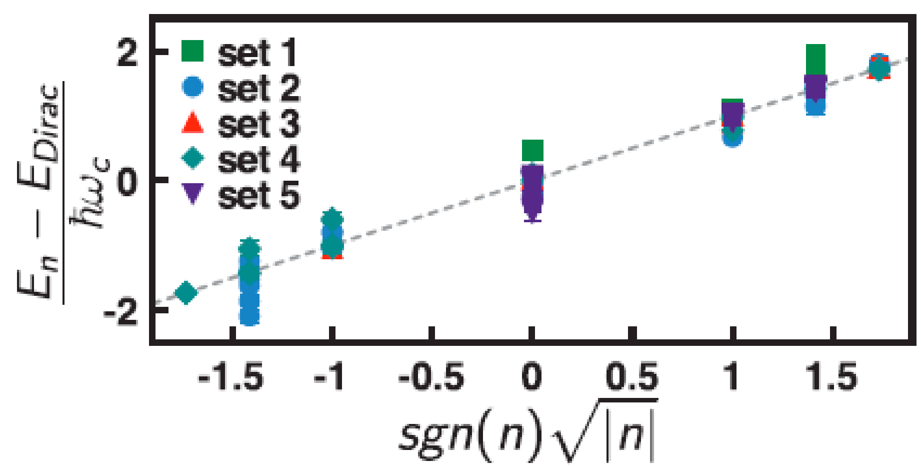
Science 329, 544 (2010)

Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles

N. Levy,[1,2*†] S. A. Burke,[1*‡] K. L. Meaker,[1] M. Panlasigui,[1] A. Zettl,[1,2] F. Guinea,[3]
A. H. Castro Neto,[4] M. F. Crommie[1,2§]





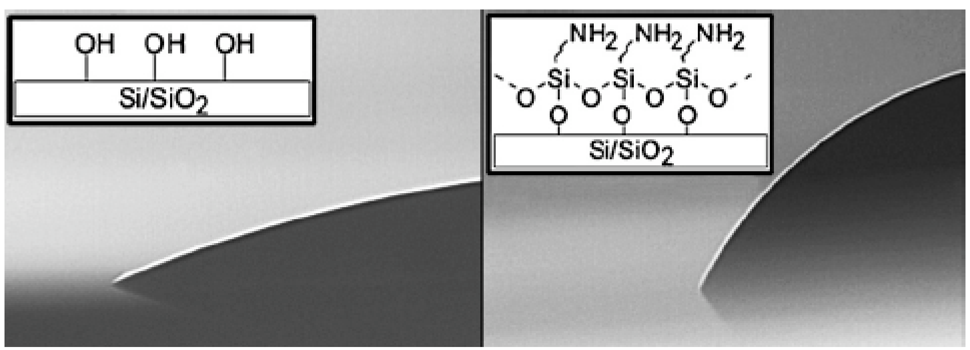


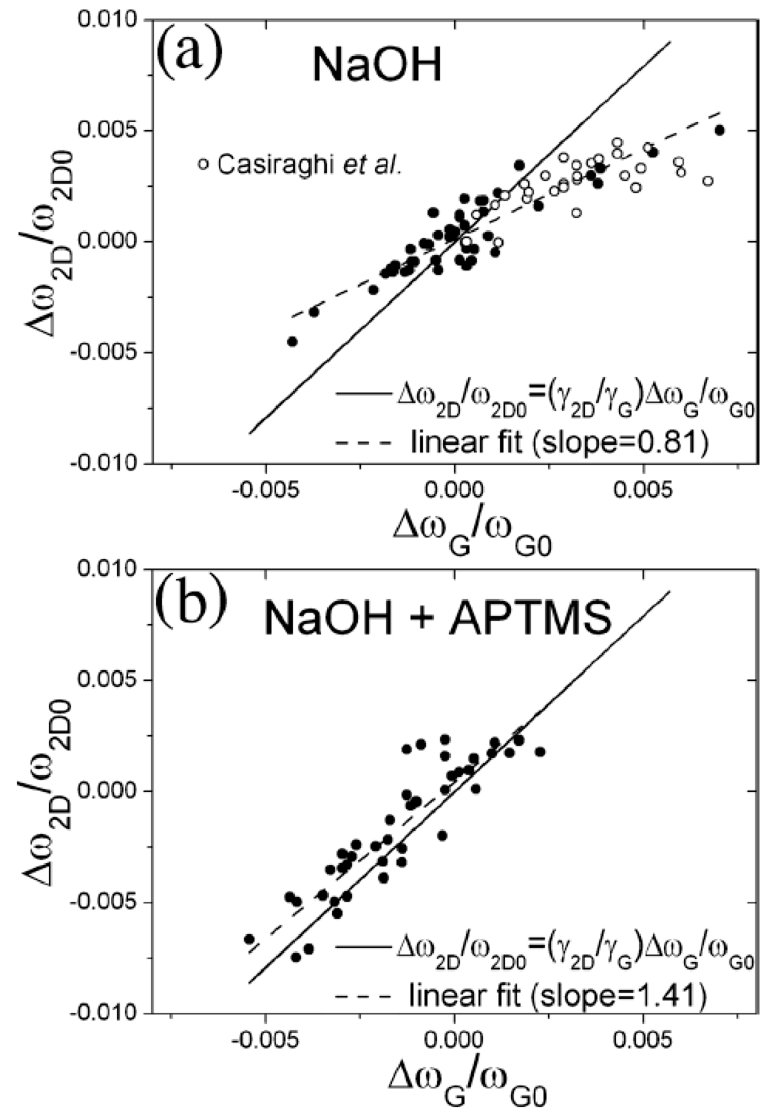
Our work: effect of the substrate

APPLIED PHYSICS LETTERS 97, 021911 (2010)

Graphene strain tuning by control of the substrate surface chemistry

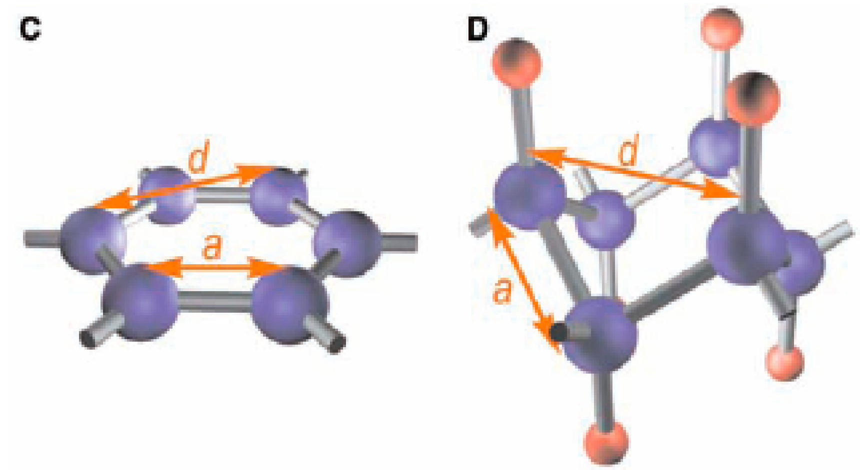
M. Bruna,[1] A. Vaira,[2] A. Battiato,[2] E. Vittone,[2] and S. Borini[1,3,a)]
[1]*Electromagnetics Division, INRIM, Strada delle Cacce 91, I-10135 Torino, Italy*
[2]*Department of Experimental Physics, Centre of Excellence "NIS," University of Torino, via. P. Giuria 1, I-10125 Torino, Italy*
[3]*Thermodynamics Division, INRIM, Strada delle Cacce 91, I-10135 Torino, Italy*

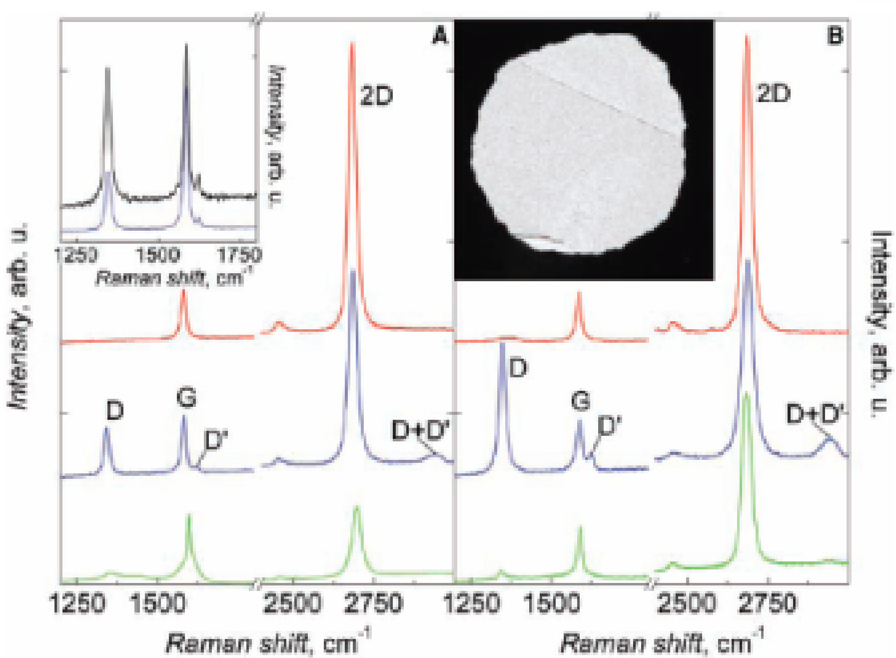


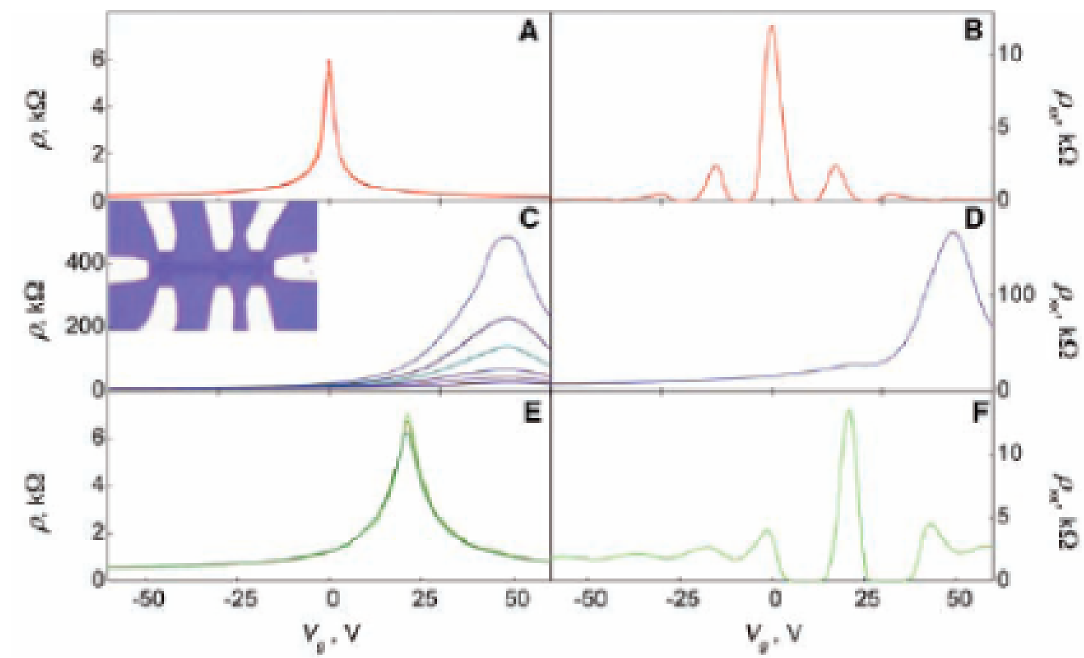


Chemical modification: graphane

Hydrogenation:
sp2 to sp3
transition



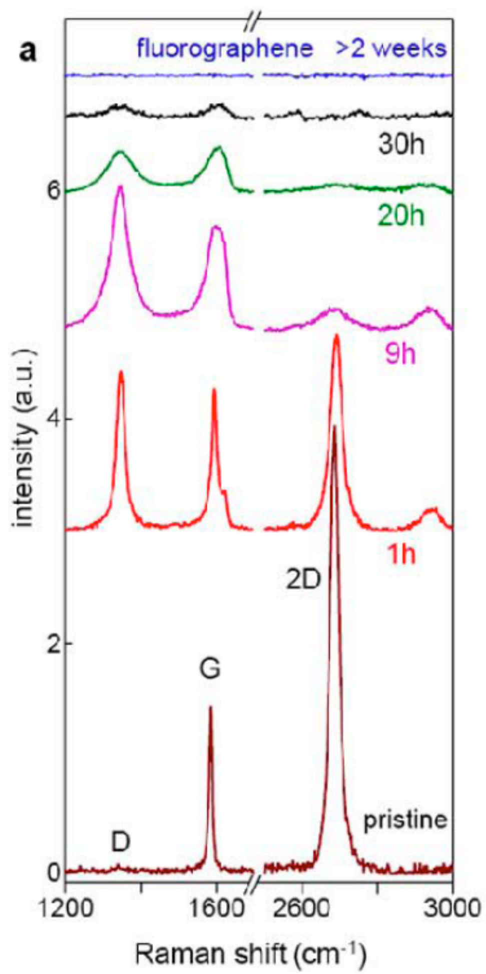


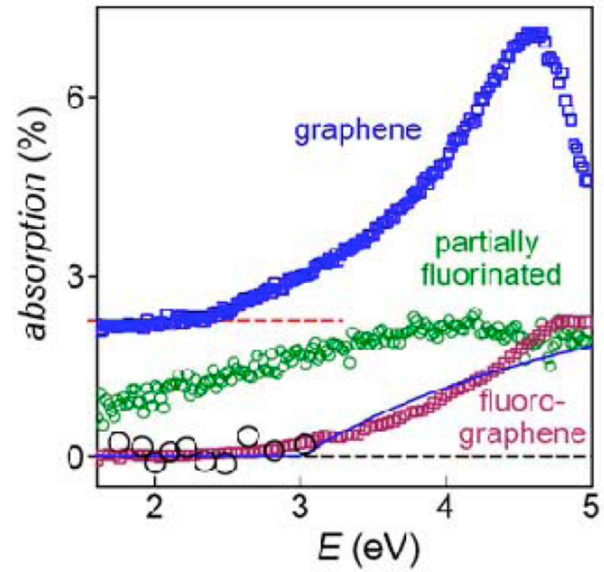


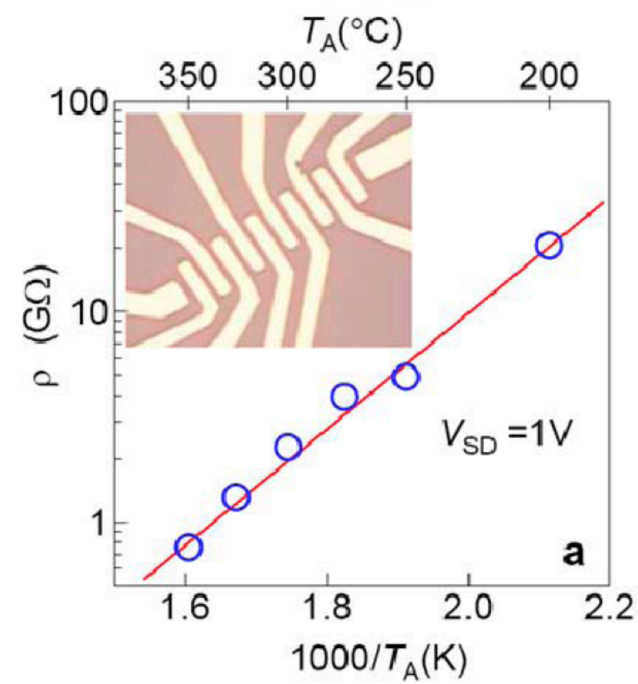
D.C. Elias et al., Science 323, 610 (2009)

Chemical modification: fluorographene

Fluorination in XeF2



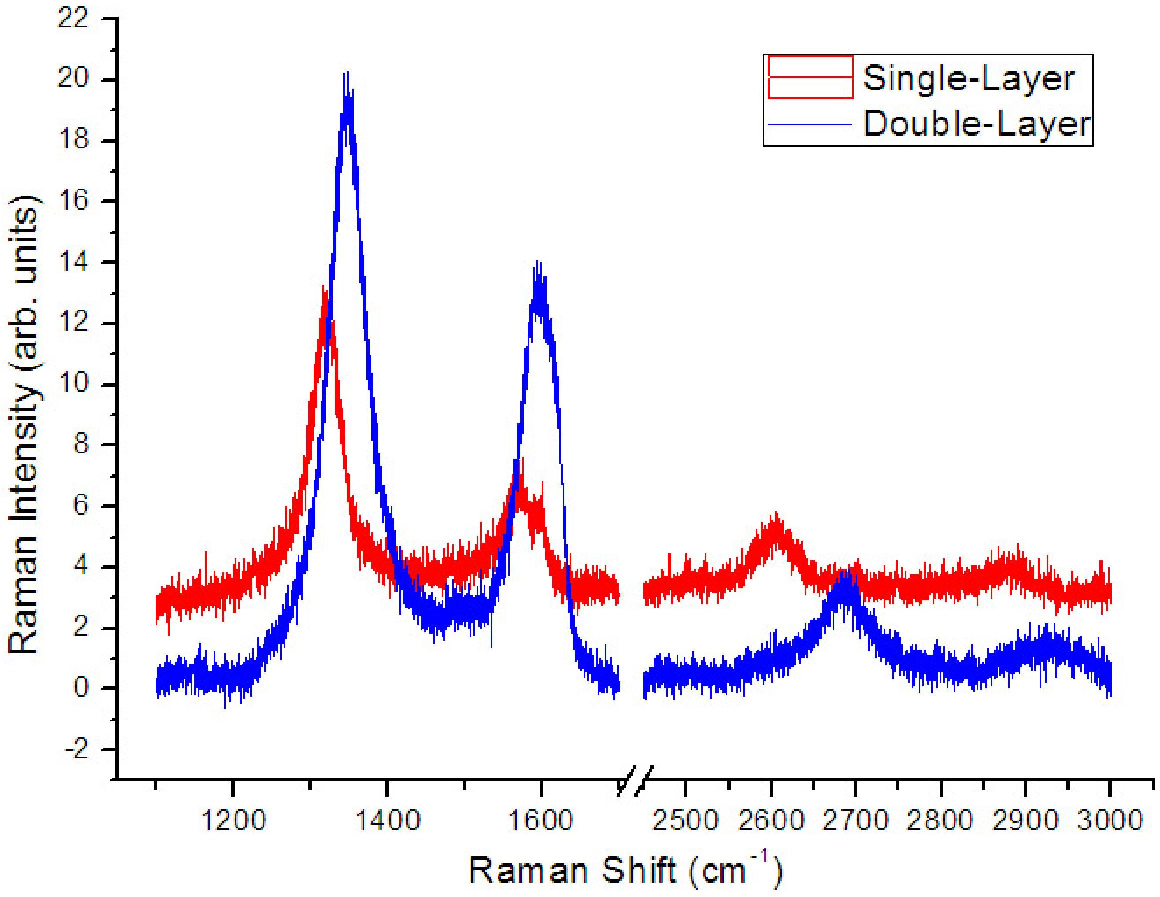




Arxiv: 1006.3016
(to appear in Small 2010)

Atomically thin wide gap insulator

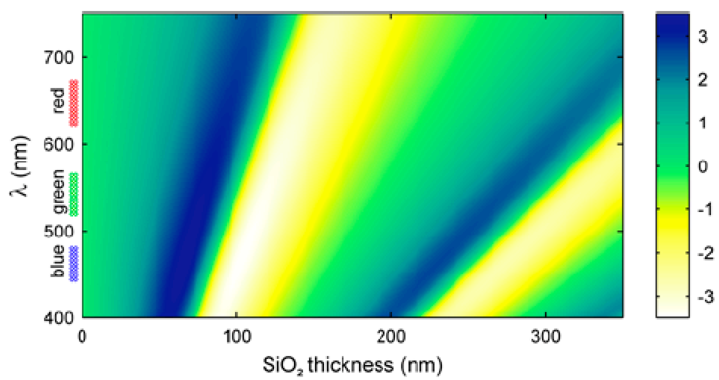
Our work: fluorinated graphene by exfoliation of electrochemically intercalated graphite

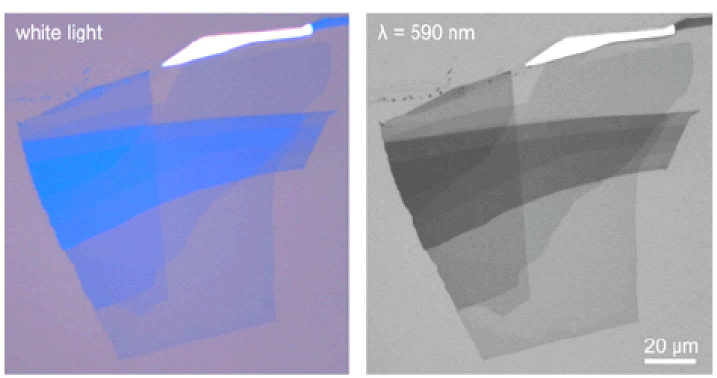


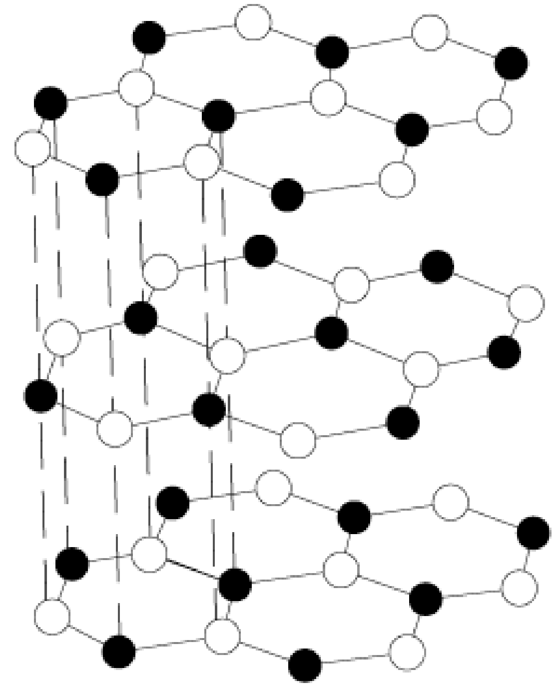
Graphene-inspired materials: exfoliated 2D-crystals

Hunting for BN monolayers

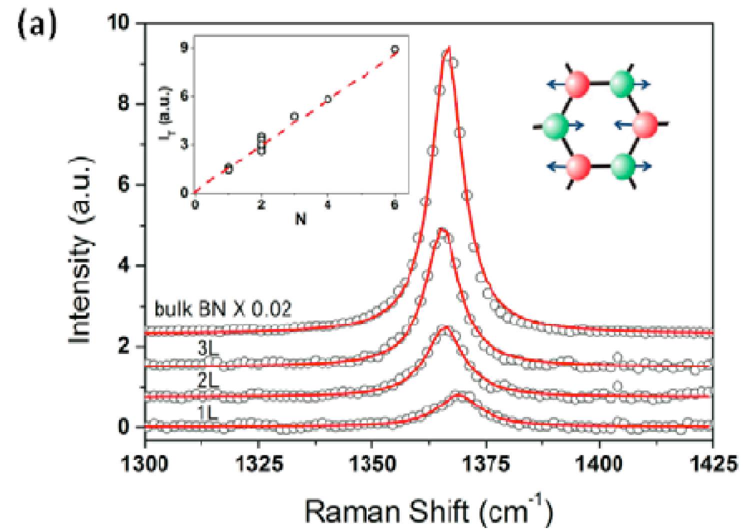
R.V. Gorbachev et al., arxiv:1008.2868







(a) Hexagonal Boron Nitride

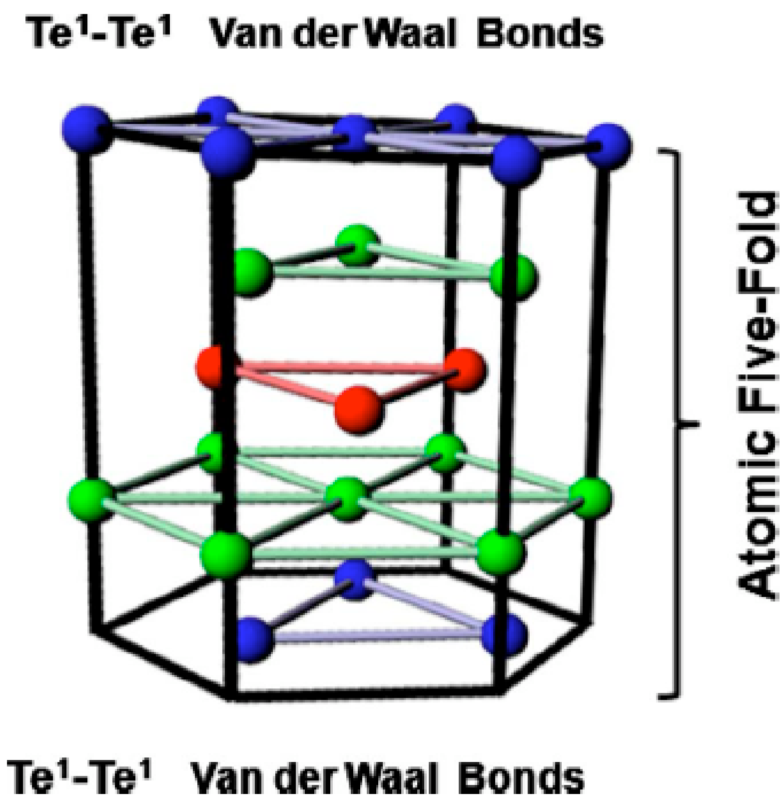


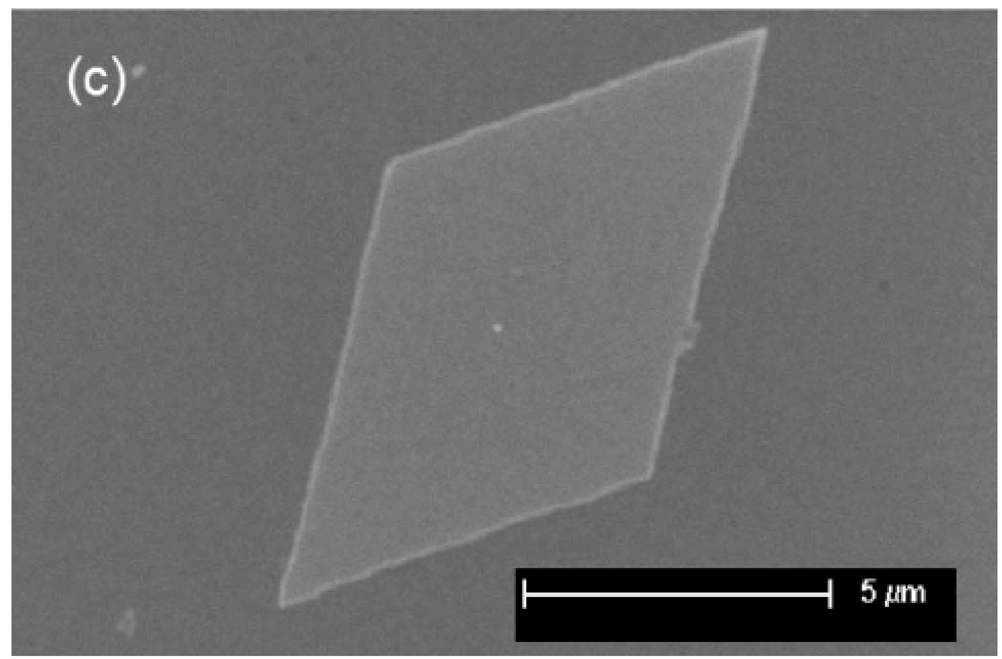
Graphene-inspired materials: exfoliated 2D-crystals

Appl. Phys. Lett. **96**, 053107 (2010)

Atomically-thin crystalline films and ribbons of bismuth telluride

Desalegne Teweldebrhan, Vivek Goyal, Muhammad Rahman, and Alexander A. Balandin



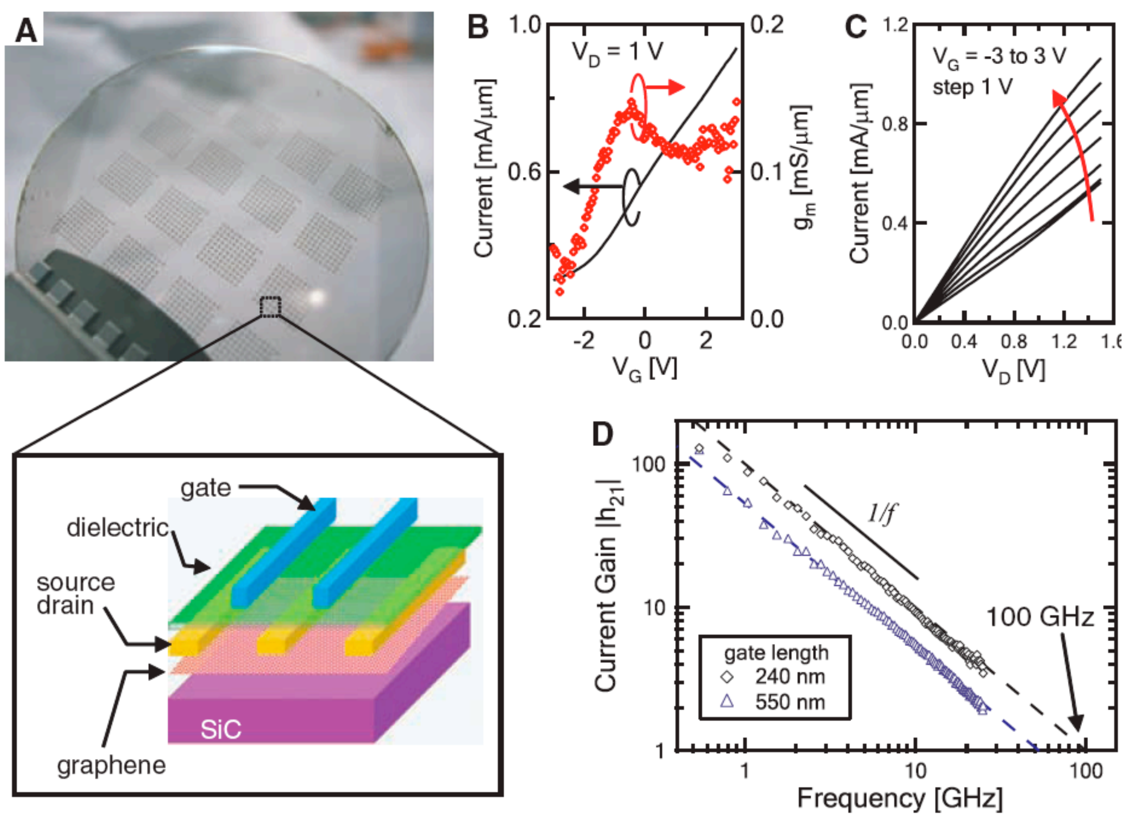


Graphene Applications: Electronics (IBM work)

Science 327, 662 (2010)

100-GHz Transistors from Wafer-Scale Epitaxial Graphene

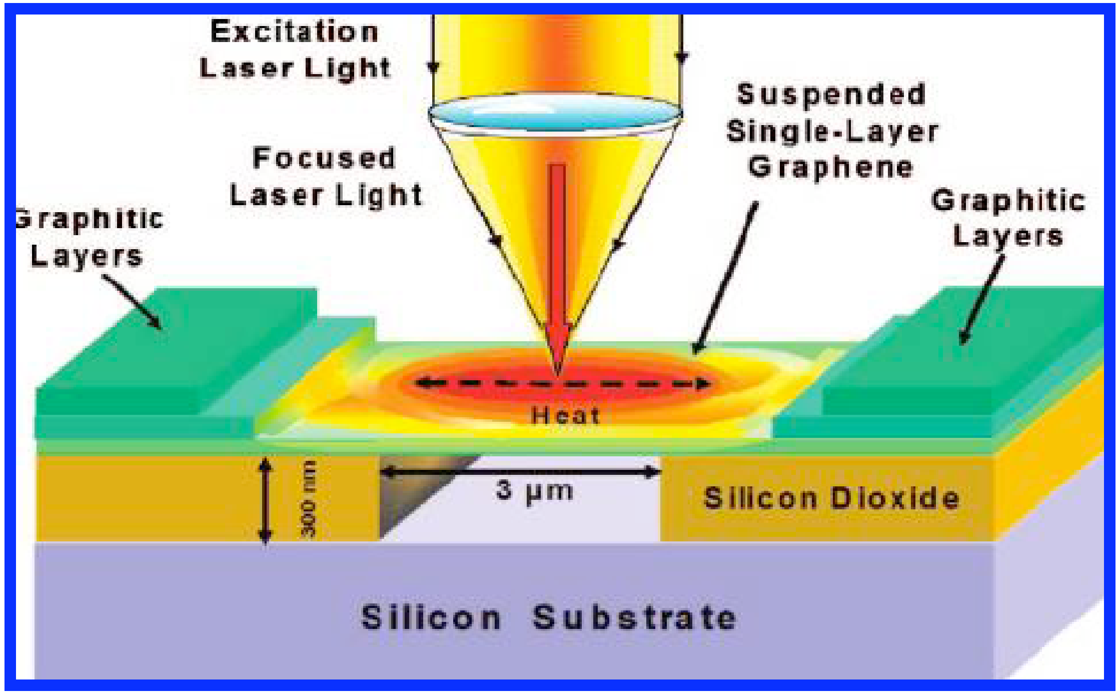
Y.-M. Lin,* C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H.-Y. Chiu, A. Grill, Ph. Avouris*



The key attractions of graphene are its outstanding carrier mobility, the good transconductance of graphene devices, and the ultimate thinness and stability of the material.

[Avouris, Nano Lett. (2010)]

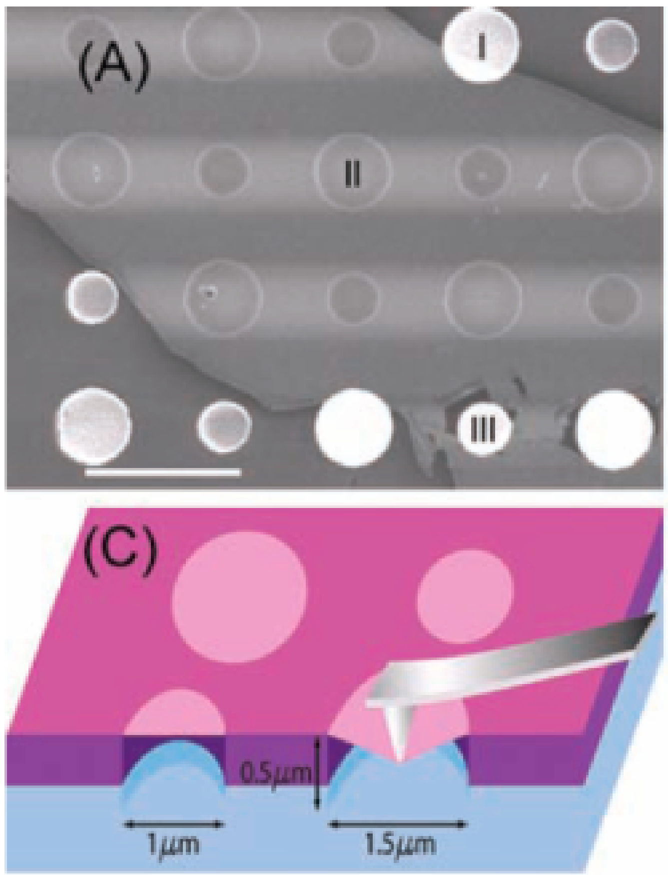
Thermal properties

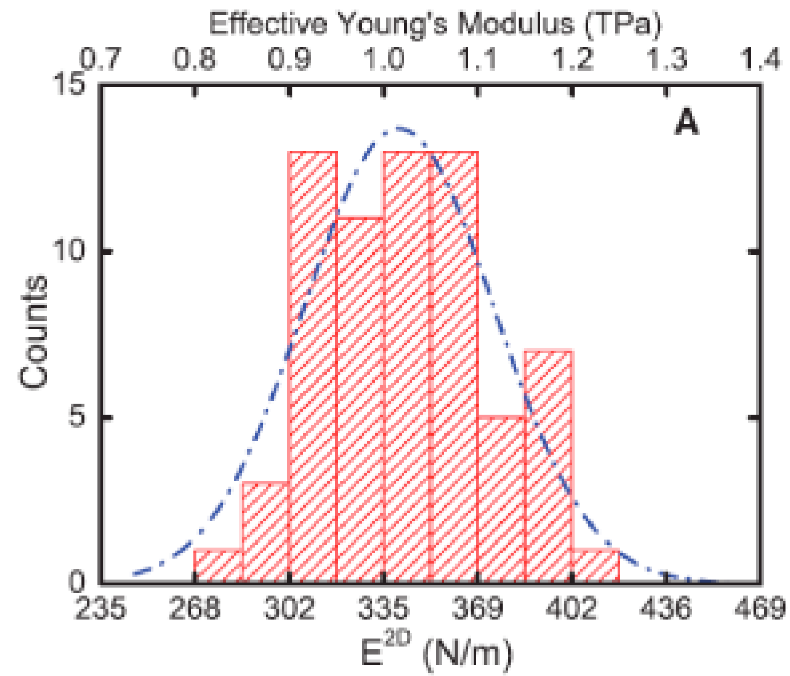


RT thermal conductivity $\sim(4.84 \pm 0.44) \times 10^3$ to $(5.30 \pm 0.48) \times 10^3$ W/mK

A.A. Balandin et al., Nano Lett. 8, 902 (2008)

Mechanical properties





Measured Young modulus: 1 TPa

Lee et al, Science 321, 385 (2008)

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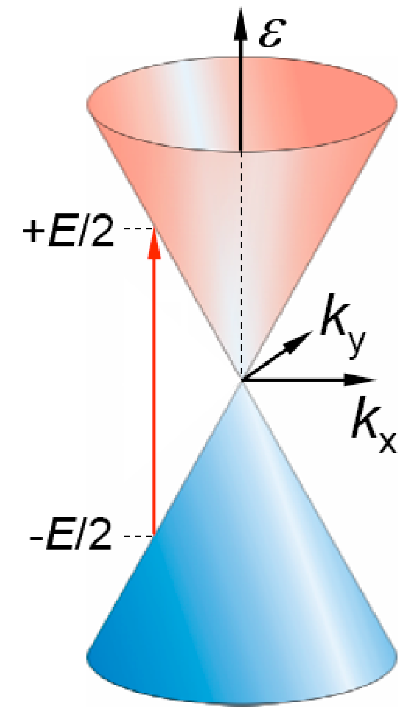
C. Cassiago, L. Callegaro, E. Gasparotto: QHE measurements

R. Rocci: technical help

"ULQHE" project: money

Nanofacility Piemonte: EBL process

Graphene opacity



electric field $\vec{\Theta}$

frequency ω

incident energy flux W_i is given by $W_i = \dfrac{c}{4\pi}|\Theta|^2$

absorbed energy $W_a = \eta\hbar\omega$

number η of such absorption events per unit time

using Fermi's golden rule $\eta = (2\pi/\hbar)|M|^2 D$

M is the matrix element for the interaction between light and Dirac fermions

For 2D Dirac fermions $D(\hbar\omega/2) = \hbar\omega/\pi\hbar^2 v_F^2$ density of states at $\varepsilon = E/2 = \hbar\omega/2$

$$\hat{H}_{int} = -v_F\vec{\sigma}\cdot\frac{e}{c}\vec{A} = v_F\vec{\sigma}\cdot\frac{e}{i\omega}\vec{\Theta} \qquad |M|^2 = |\langle f|\, v_F\vec{\sigma}\cdot\frac{e}{i\omega}\vec{\Theta}\,|i\rangle|^2 = \frac{1}{8}e^2 v_F^2\frac{|\Theta|^2}{\omega^2}$$