

Growth, characterization and applications of new two dimensional materials.

R. Larciprete,

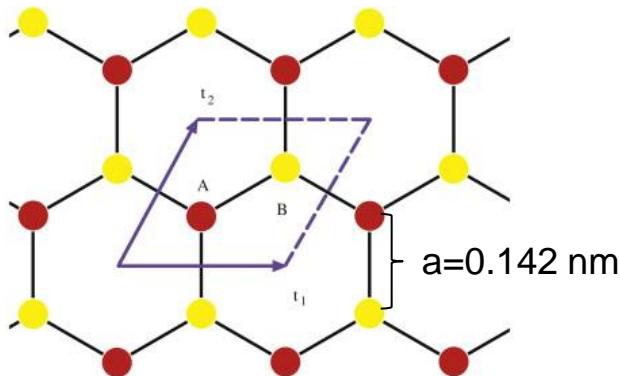
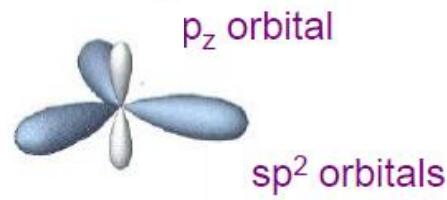
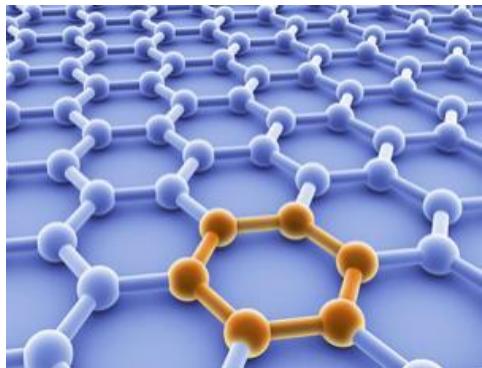
CNR-Istituto del Sistemi Complessi, Roma

e

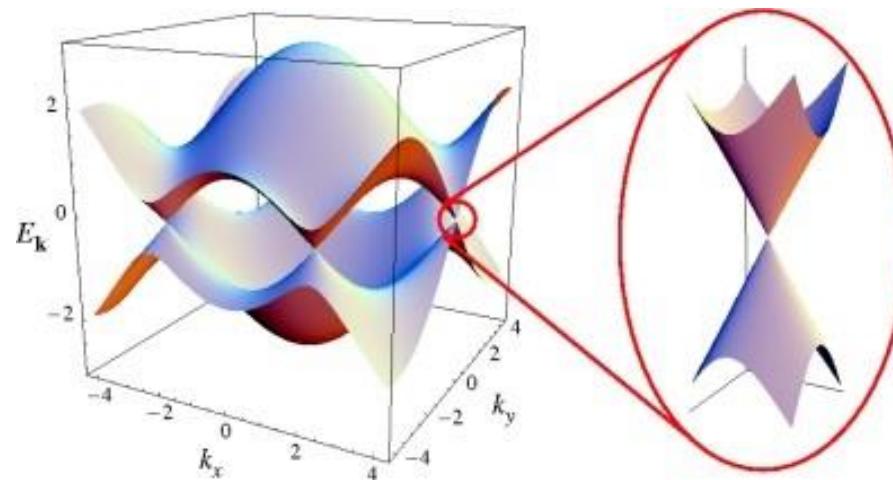
LNF-INFN Frascati



Monolayer graphene properties



semi-metal or zero-gap semiconductor



at the Dirac points the dispersion is linear and electrons and holes behave like relativistic particles with Fermi velocity $v_F \sim 10^6 \text{ m/s}$

transport is ambipolar

graphene lacks a bandgap around the Fermi level

Graphene-like materials

- New materials

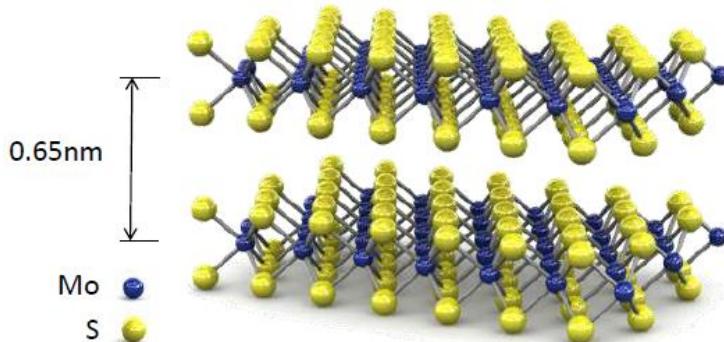
2D layer of IV group elements:
silicene, germanene

- Materials well known in their 3D form

Nitrides **h-BN**

Transition metal dichalcogenides (**MoS₂, WS₂...**)
MX₂ (M: Mo, W, Nb, Re, Ni, or V) (X: S, Se, or Te)

Oxides **MoO₃, V₂O₅**

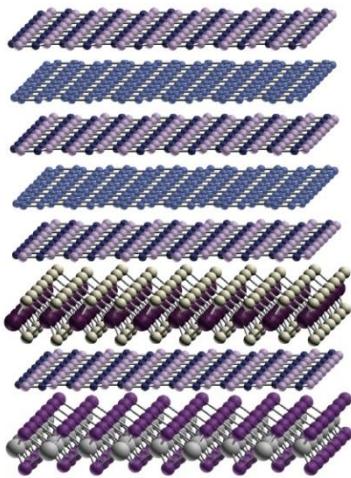


a	H	MX ₂ M = Transition metal X = Chalcogen												He							
	Li	Be	Na	Mg	3	4	5	6	7	8	9	10	11	12	Al	Si	C	N	O	F	Ne
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr				
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe				
Cs	Ba	La - Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn				
Fr	Ra	Ac - Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo				

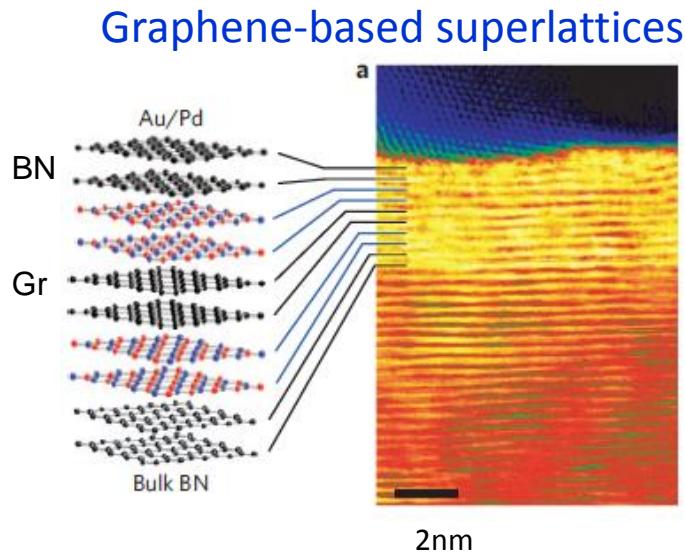
Electrical property	Material
metallic, CDW, superconducting	NbSe ₂ , NbS ₂ , NbTe ₂ TaS ₂ , TaSe ₂ , TaTe ₂
semimetallic	TiSe ₂
semiconducting	MoS ₂ , MoSe ₂ , WS ₂ , WSe ₂ , MoTe ₂ , WTe ₂

1.2 eV band gap (bulk);
1.8 eV direct gap (single layer)

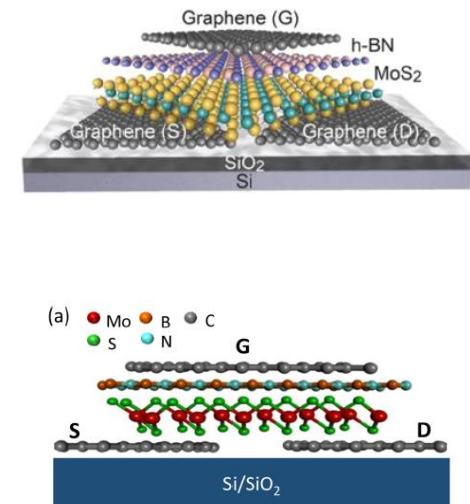
Graphene: Materials in the Flatland



K. S. Novoselov,
Rev. Mod. Phys. 83, 837 2011

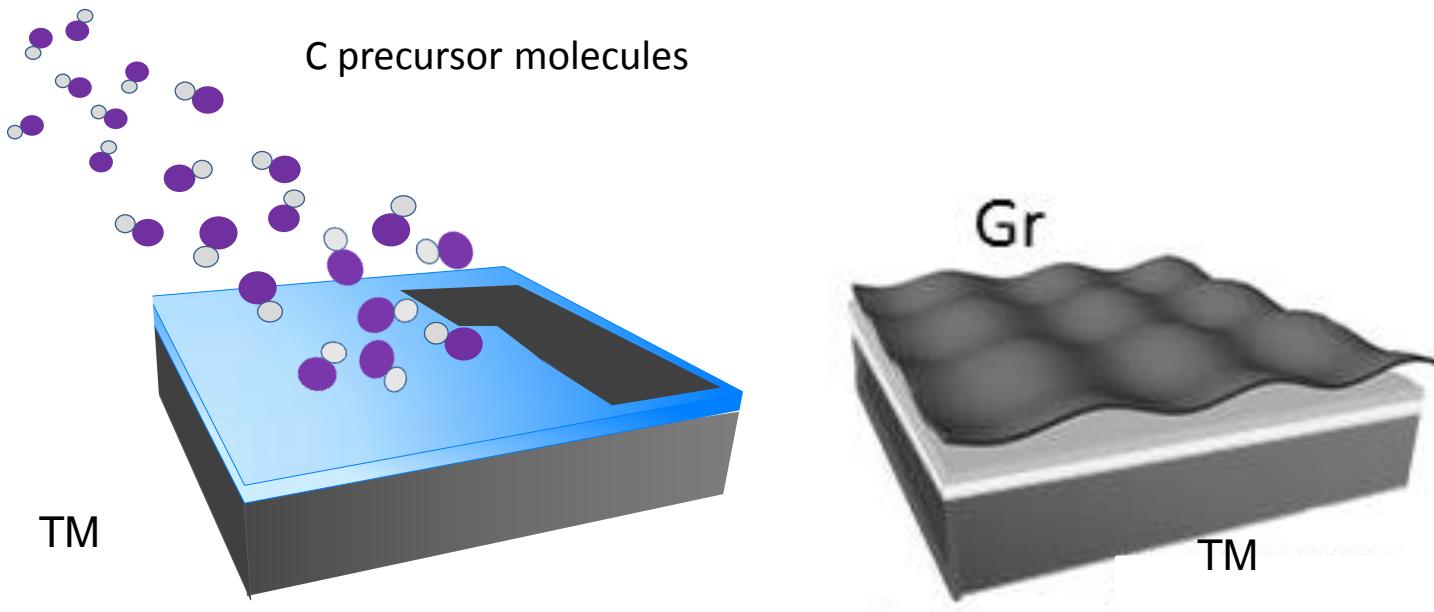


S. Haigh et al. Nat. Mat. 11 764 (2012)



Roy et al., ACS Nano
6 (2014) 6259

Epitaxial graphene on TM metals

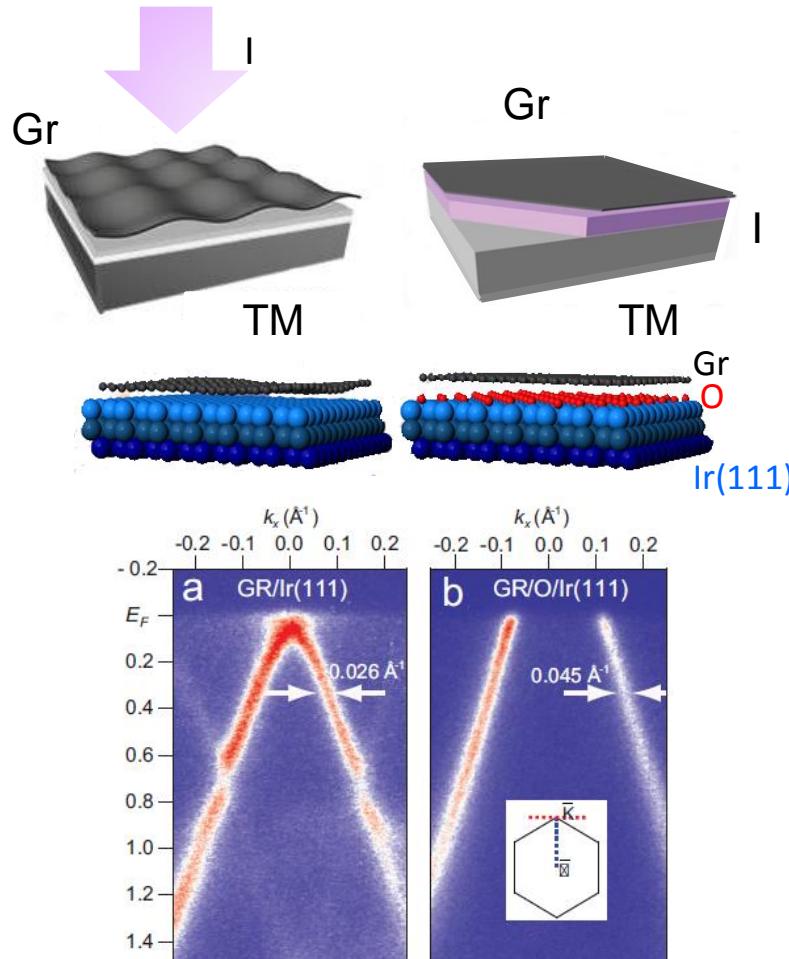


(Ir, Ru, Pt, Re, Rh, Ni, Fe, Cu, PtRh, NiAl,)

Large area graphene
Self-limiting growth
Low defect density

Intercalation of below epitaxial graphene

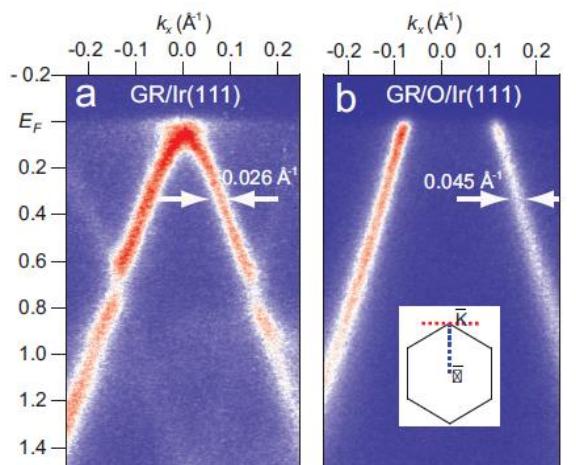
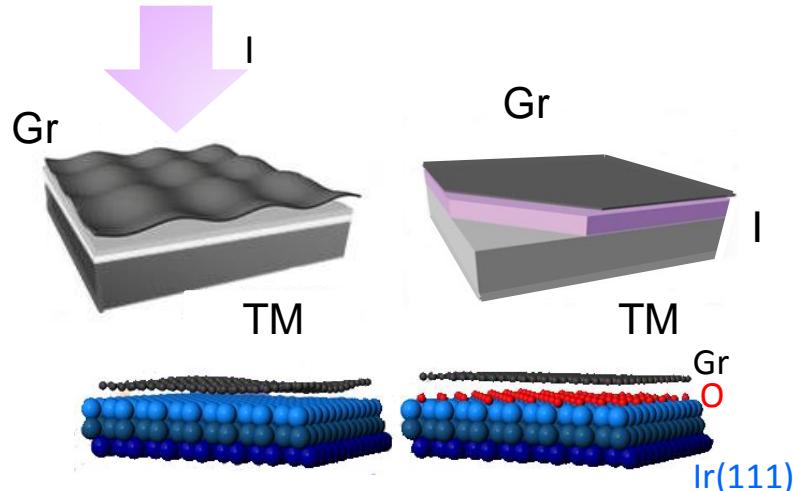
Decoupling Gr by O intercalation



Larciprete et al ACS Nano 6, 9551 (2012)

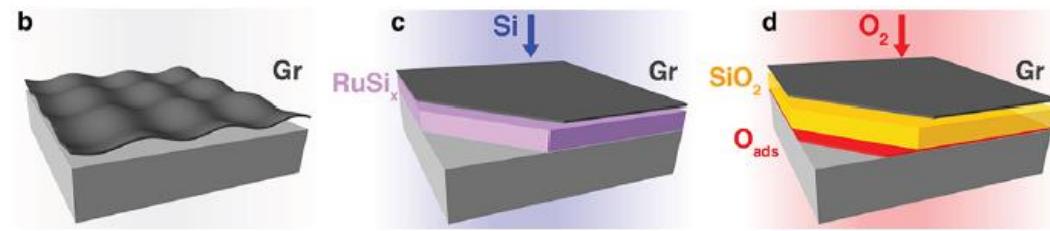
Intercalation of below epitaxial graphene

Decoupling Gr by O intercalation



Larciprete et al ACS Nano 6, 9551 (2012)

Material synthesis below graphene

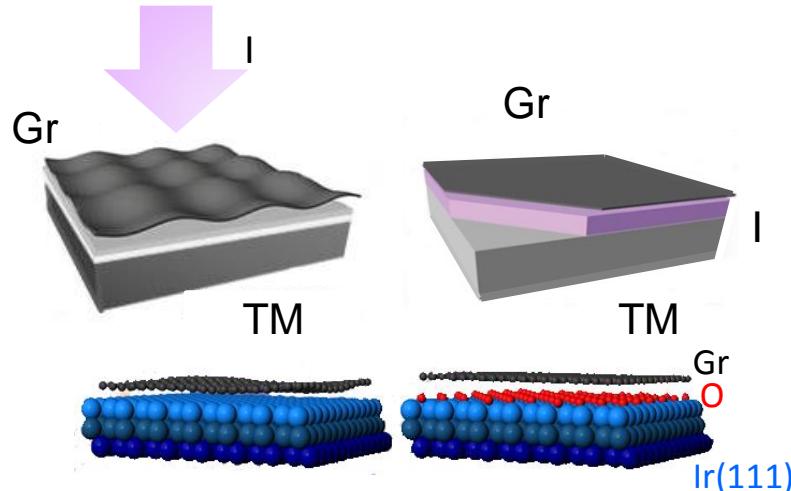


Gr/SiO₂/Ru(0001)

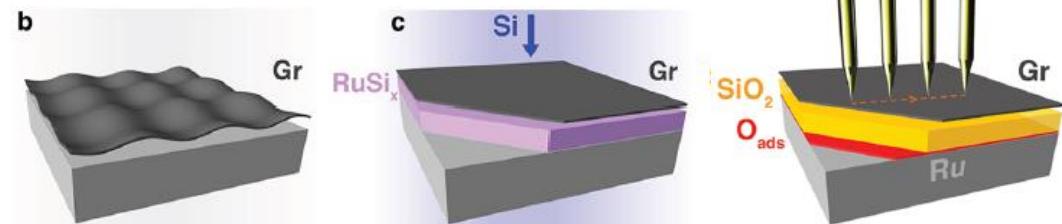
Lizzit, RL, et al. Nano Lett. 12, 4503 (2012)

Intercalation of below epitaxial graphene

Decoupling Gr by O intercalation

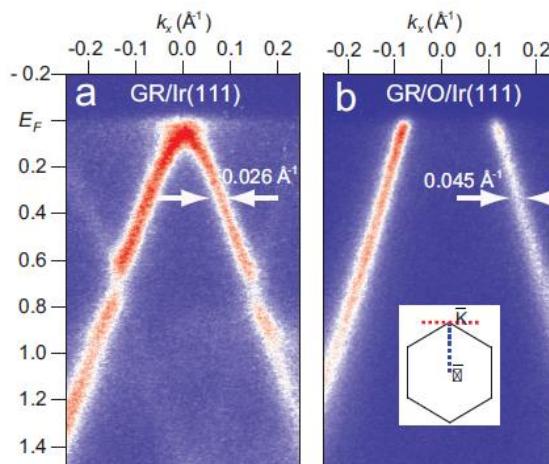


Material synthesis below graphene



Gr/SiO₂/Ru(0001)

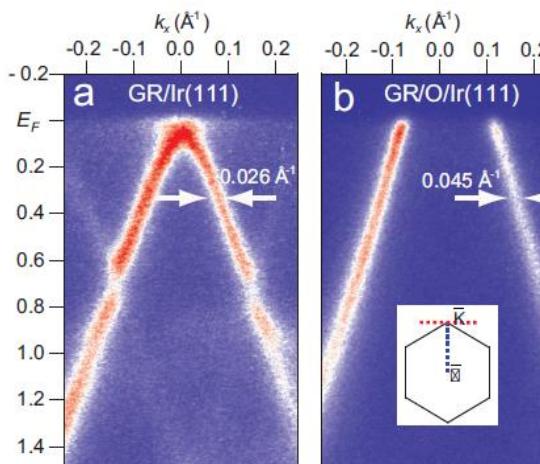
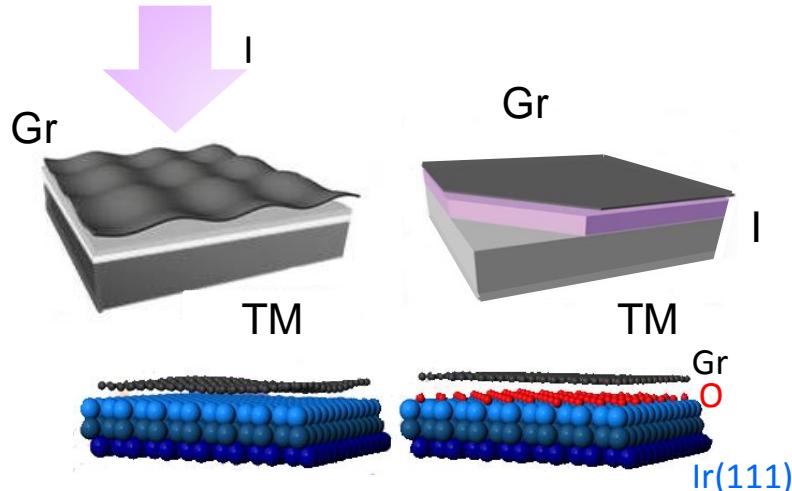
Lizzit, RL, et al. Nano Lett. 12, 4503 (2012)



Larciprete et al ACS Nano 6, 9551 (2012)

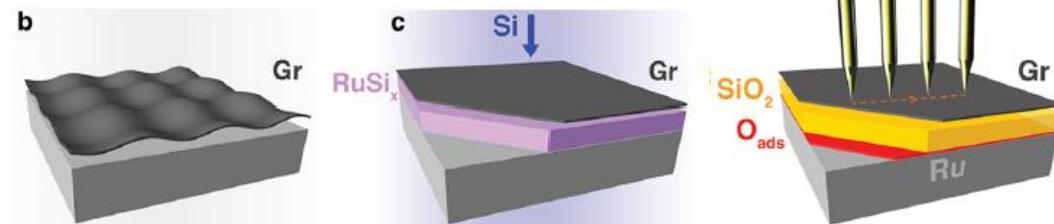
Intercalation of below epitaxial graphene

Decoupling Gr by O intercalation



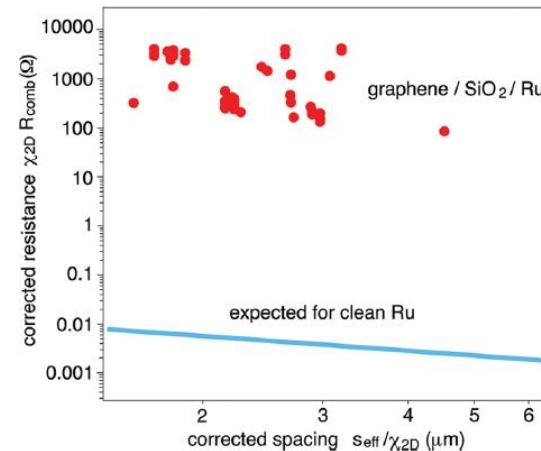
Larciprete et al ACS Nano 6, 9551 (2012)

Material synthesis below graphene



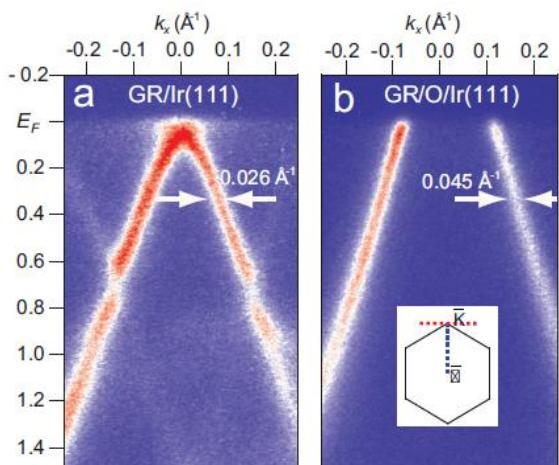
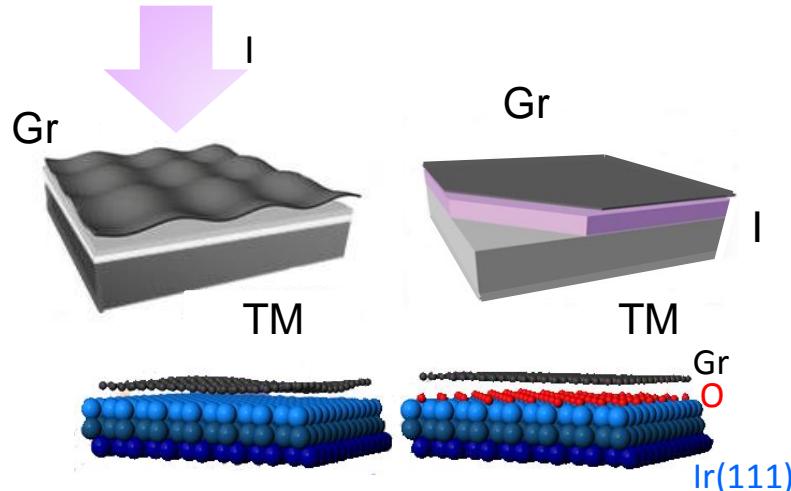
Gr/SiO₂/Ru(0001)

Lizzit, RL, et al. Nano Lett. 12, 4503 (2012)



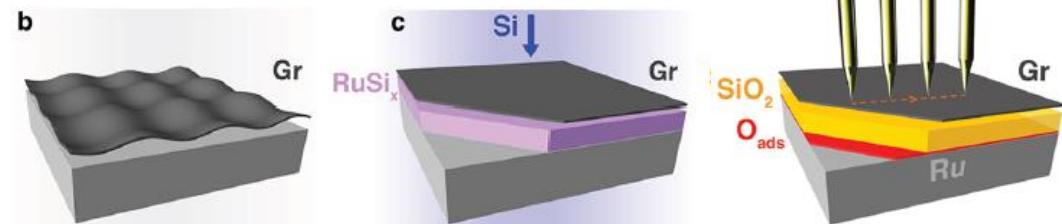
Intercalation of below epitaxial graphene

Decoupling Gr by O intercalation



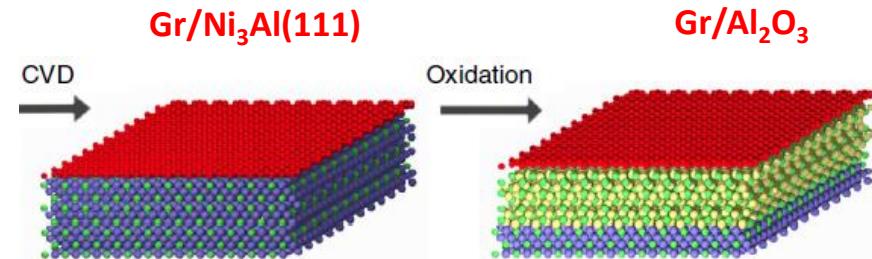
Larciprete et al ACS Nano 6, 9551 (2012)

Material synthesis below graphene



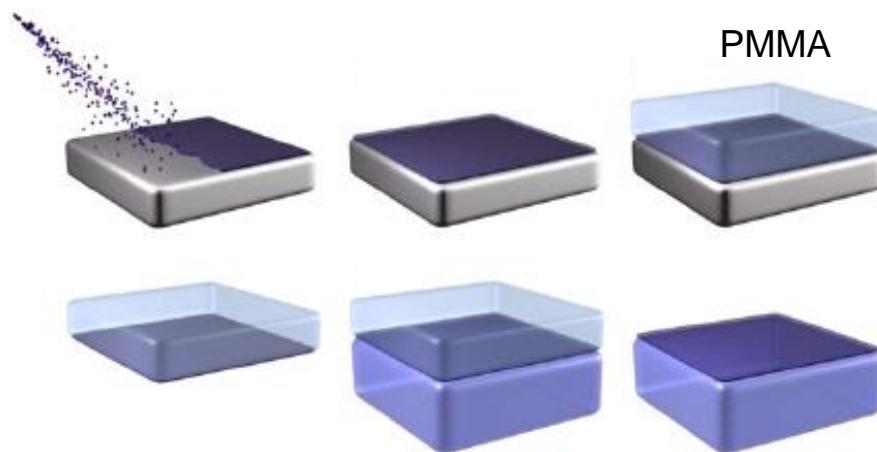
Gr/SiO₂/Ru(0001)

Lizzit, RL, et al. Nano Lett. 12, 4503 (2012)



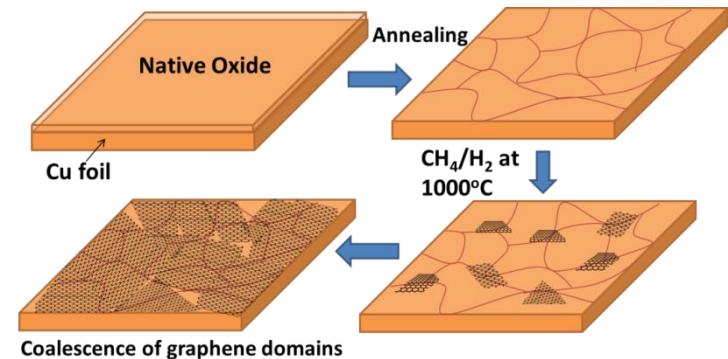
Omiciuolo, RL, et al. Nat. Comm. 5 (5062) 2014

Transfer of large area graphene

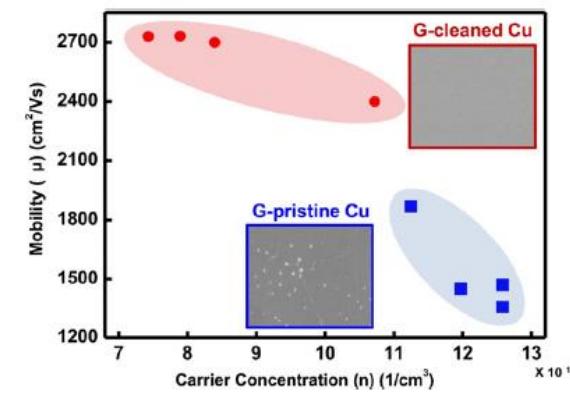
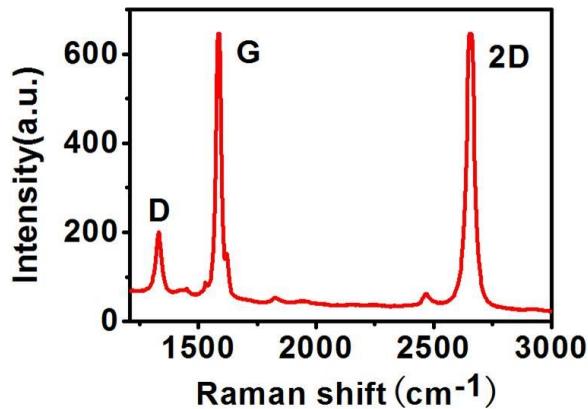


Novoselov et al, Phys. Scr. T146 014006 2012

Growth on Cu foils



Raman spectroscopy

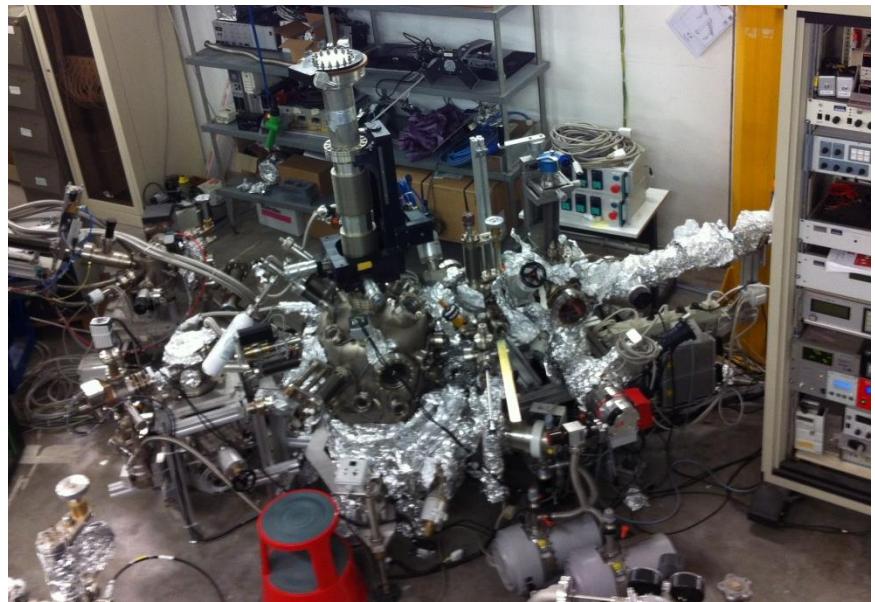
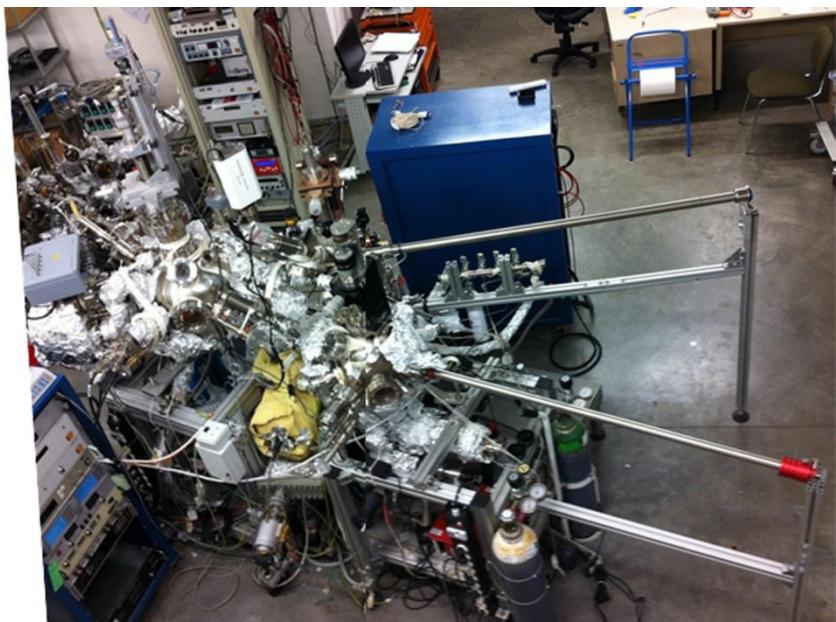


Kim et al, Nanotechnology 24 (2013) 365602

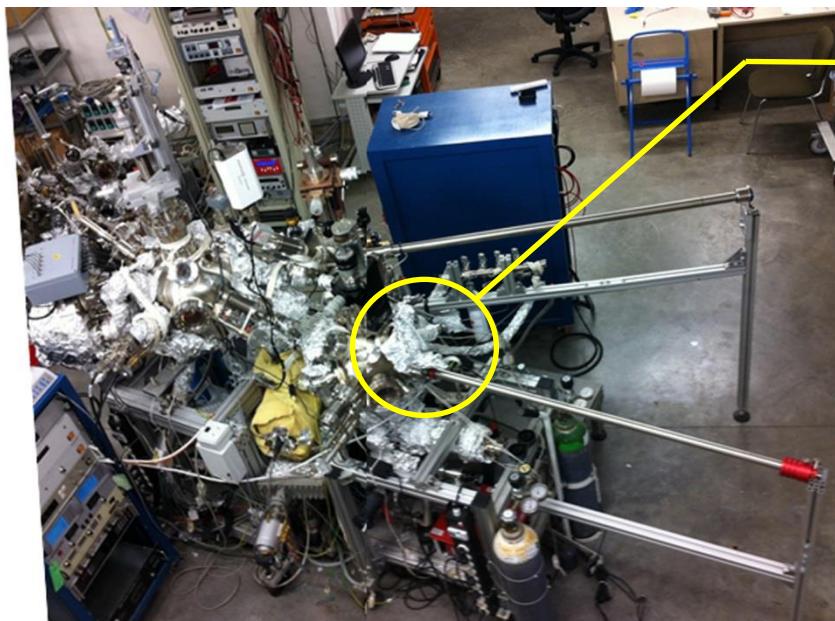
Open issues in the rise of 2D materials

- Bottom-up growth
- Thickness control (mono-, bi-, multi-layer)
- Transfer protocols
- Defect density
- Doping state
- Stability (thermal, chemical, structural)

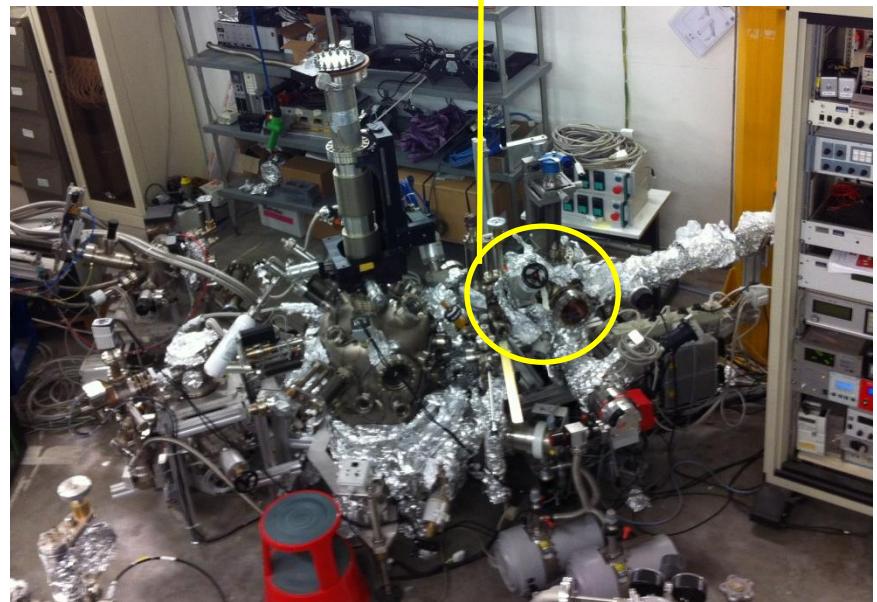
Material Science Laboratory of the INFN-LNF



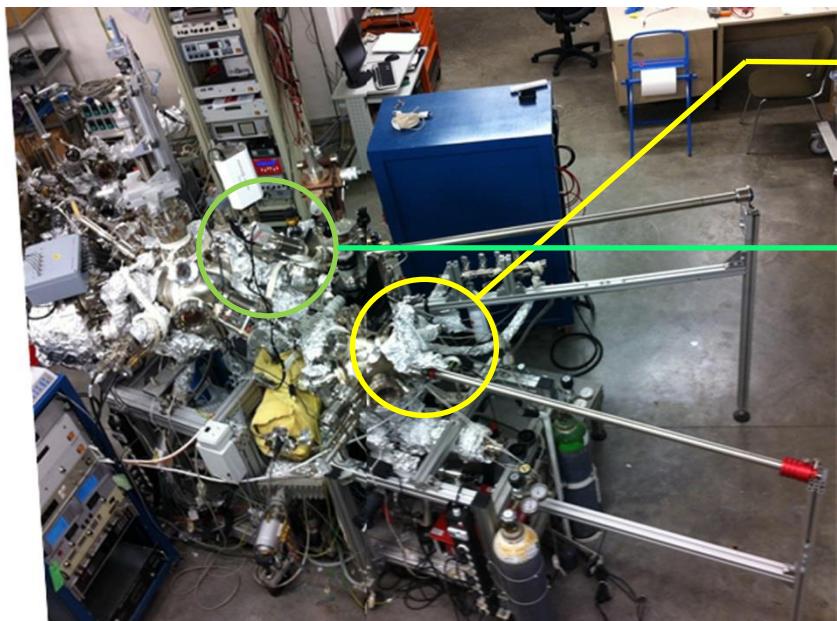
Material Science Laboratory of the INFN-LNF



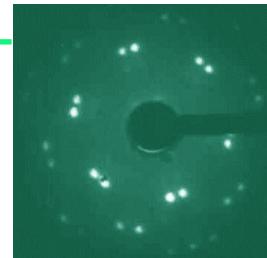
material growth (CVD, MS)



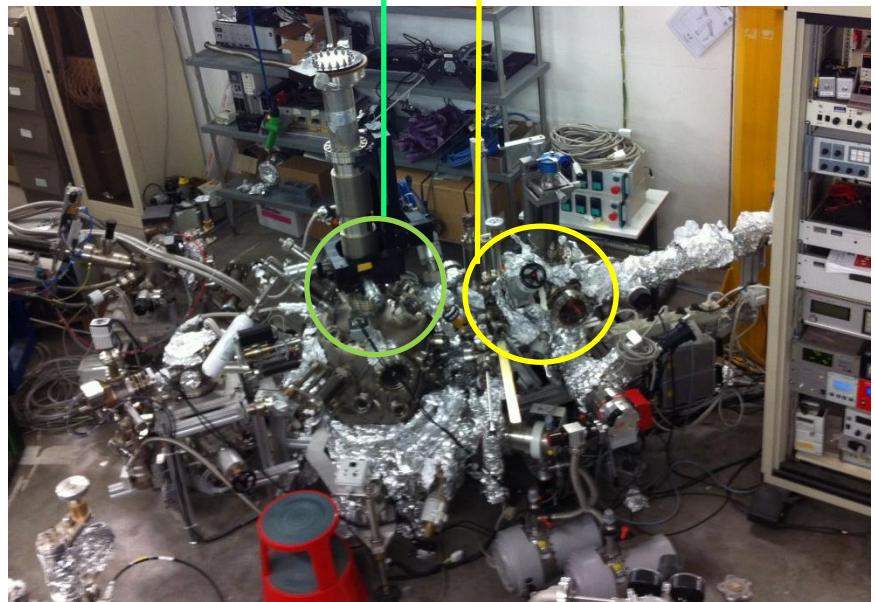
Material Science Laboratory of the INFN-LNF



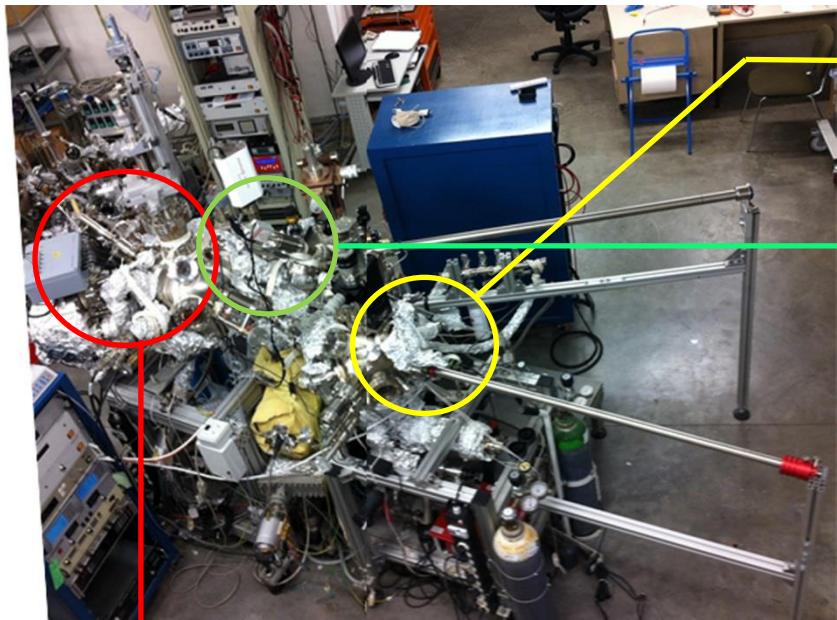
material growth (CVD, MS)



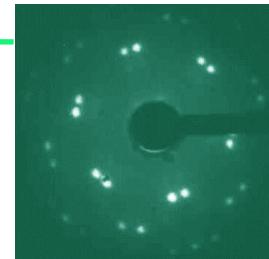
low Energy Electron Diffraction



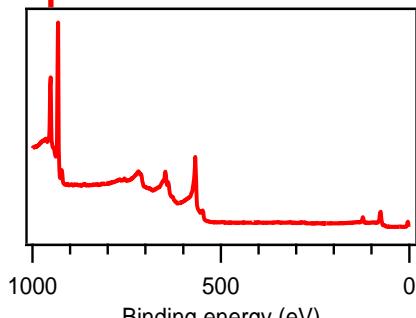
Material Science Laboratory of the INFN-LNF



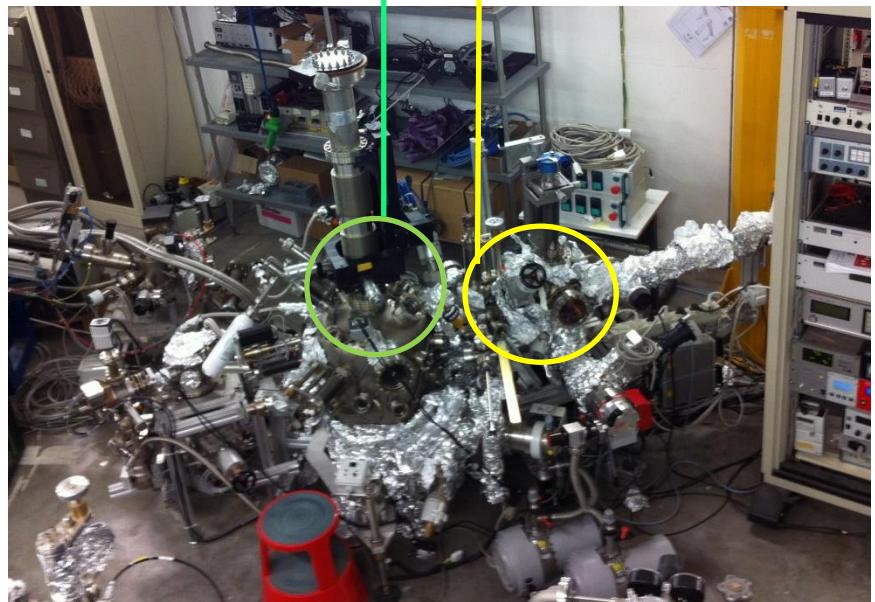
material growth (CVD, MS)



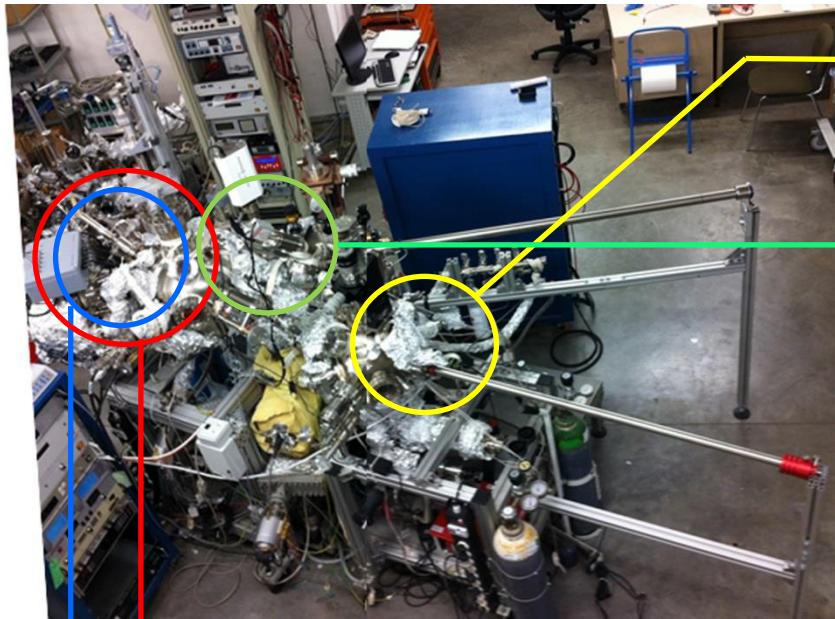
low Energy Electron Diffraction



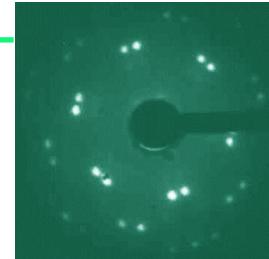
X-ray photoelectron
spectroscopy



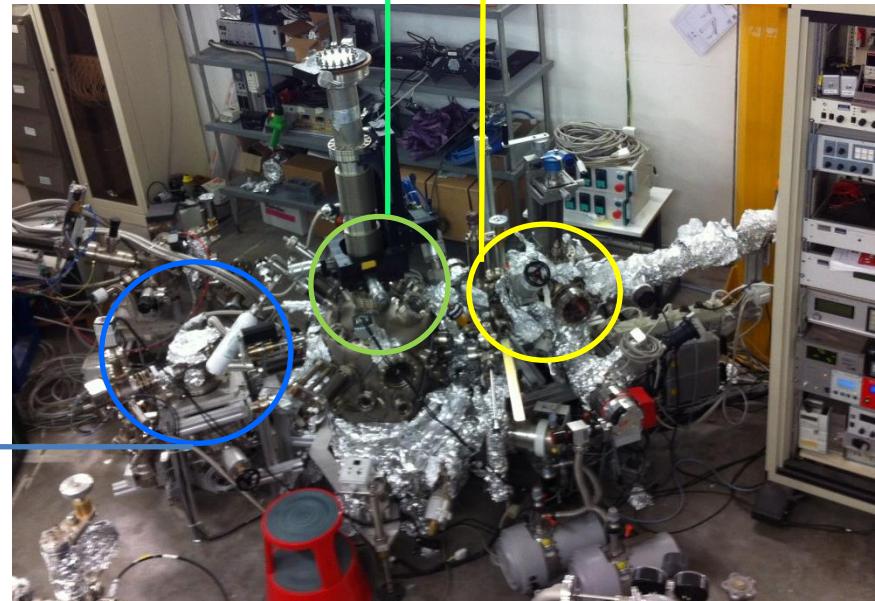
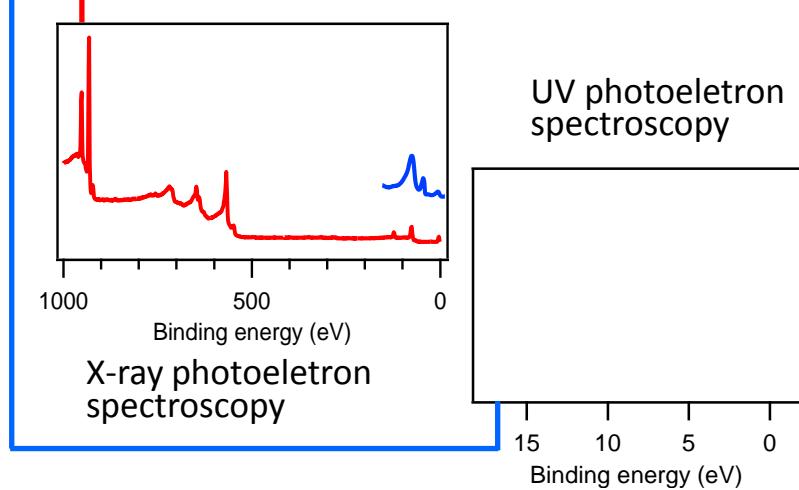
Material Science Laboratory of the INFN-LNF



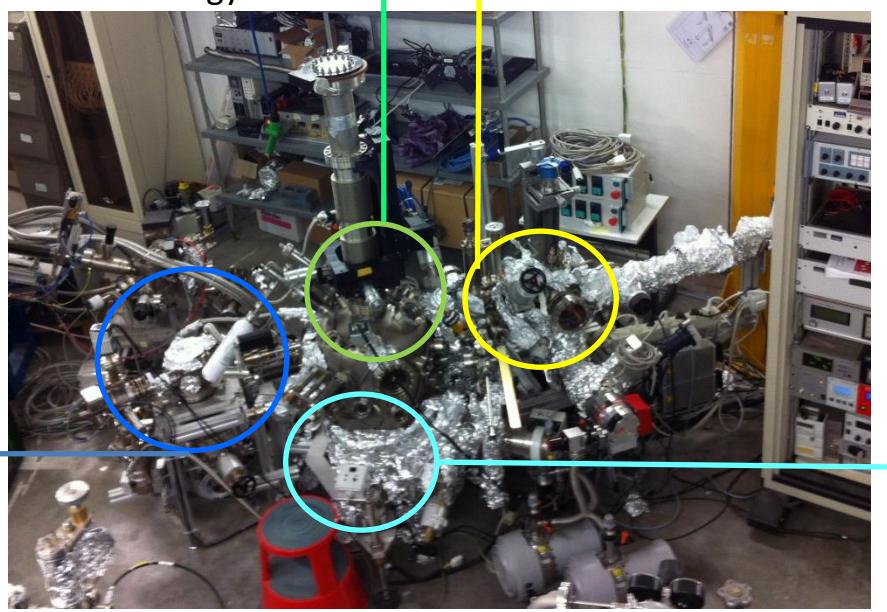
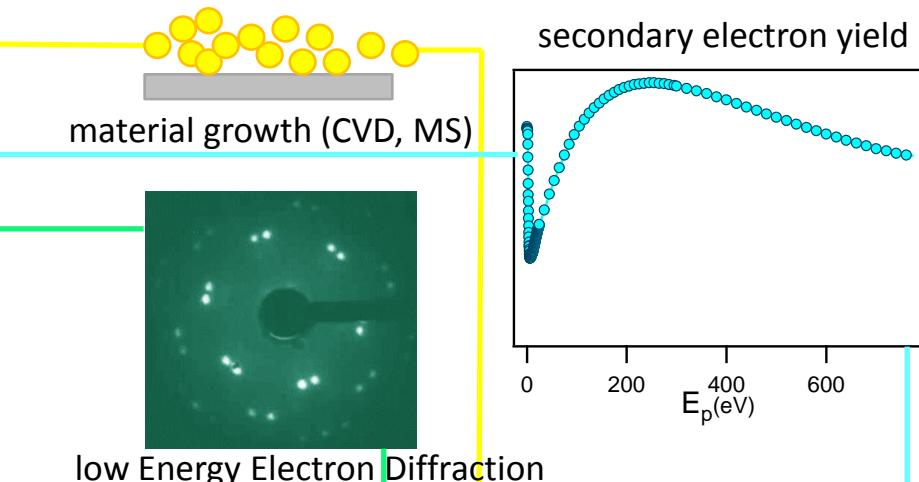
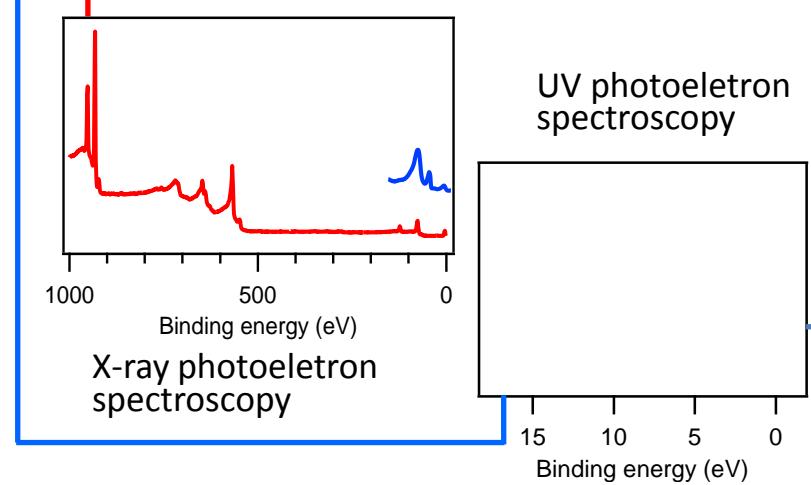
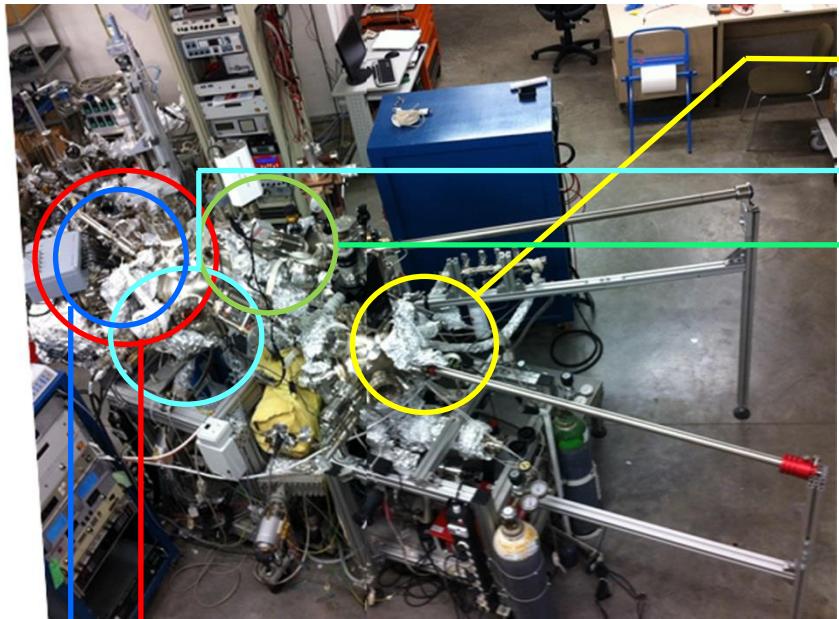
material growth (CVD, MS)



low Energy Electron Diffraction

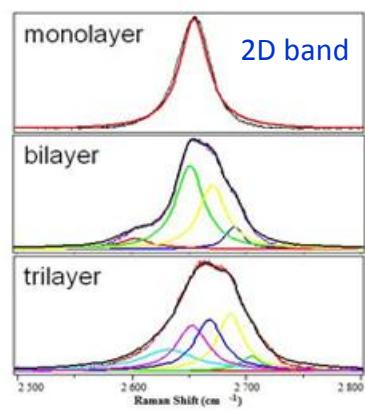
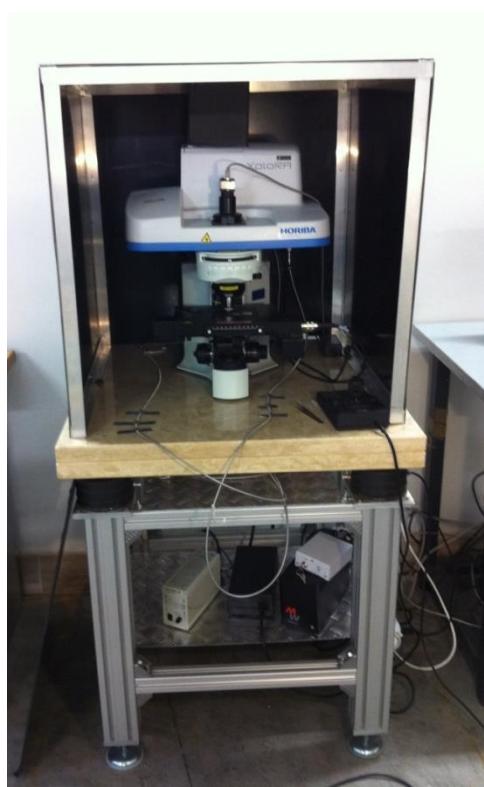


Material Science Laboratory of the INFN-LNF

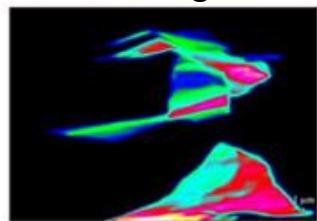


Material Science Laboratory of the INFN-LNF

Raman microscope

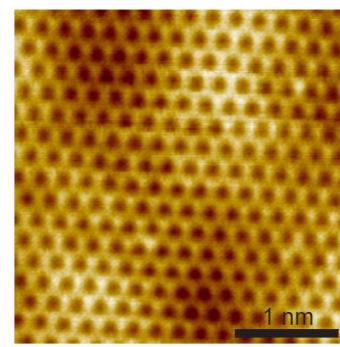
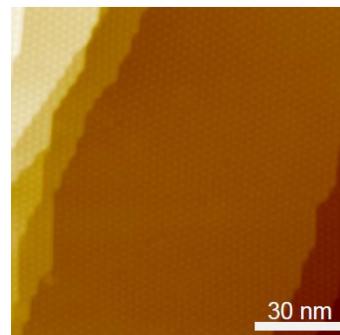


Raman image



optical image

scanning tunneling microscope



The GARFIELD Project – CSN5



Graphene Active FIllms for Electronic Devices and Radiation Detection

Alessandra Di Gaspare

GARFIELD Key concept: G-based devices for novel schemes of radiation detection

Objectives of the Project:

- Implementation of a full-capability GR platform @ LNF-INFN (Material Science Lab)
- Development of GR-based detectors for application of interest to the INFN

UNIT-1 @ LNF



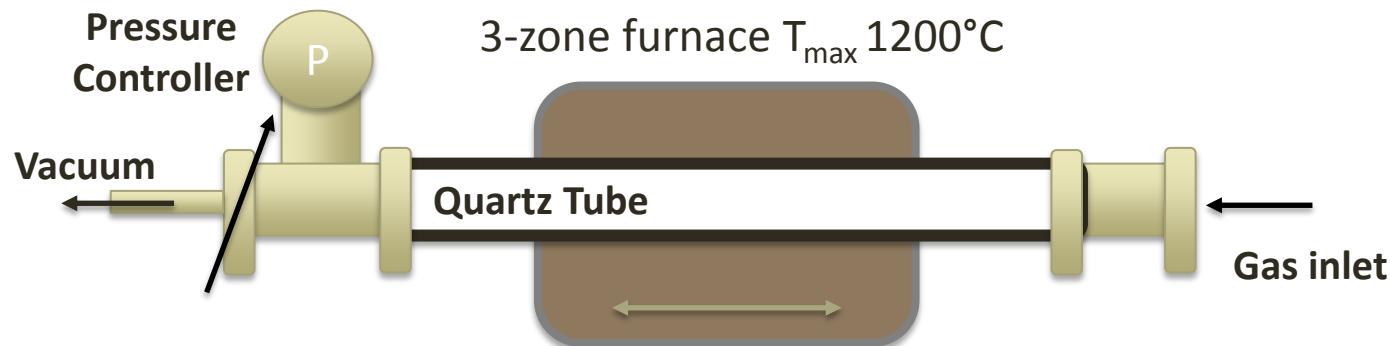
UNIT-2 @ CNR (IFN & IMM)



Fully equipped class-1000 clean-room facility
Electron Beam Lithography

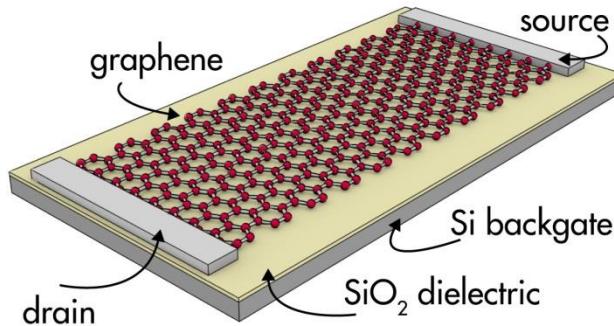
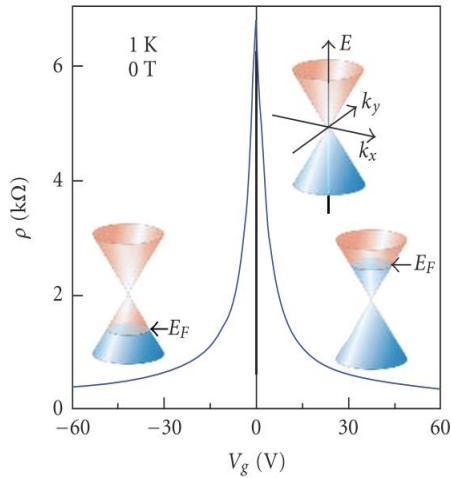
The Graphene CVD Facility @LNF

TUBE FURNACE WITH CONTROLLED ATMOSPHERE



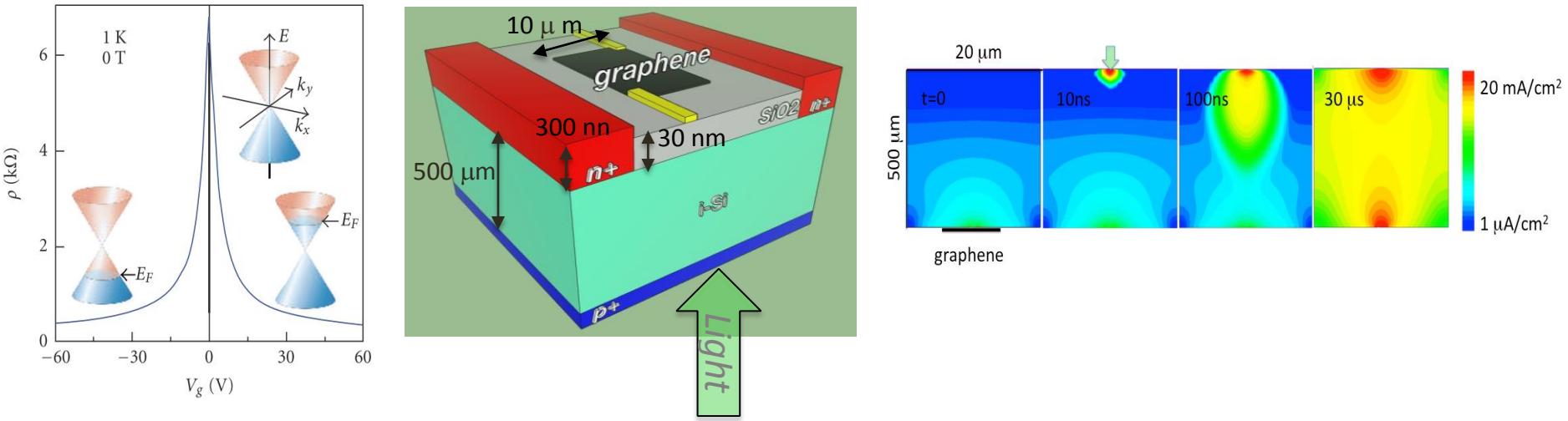
Graphene detectors

G-FET detectors: graphene as active layer; in G-FET, transient change in channel conductivity at the Dirac Point



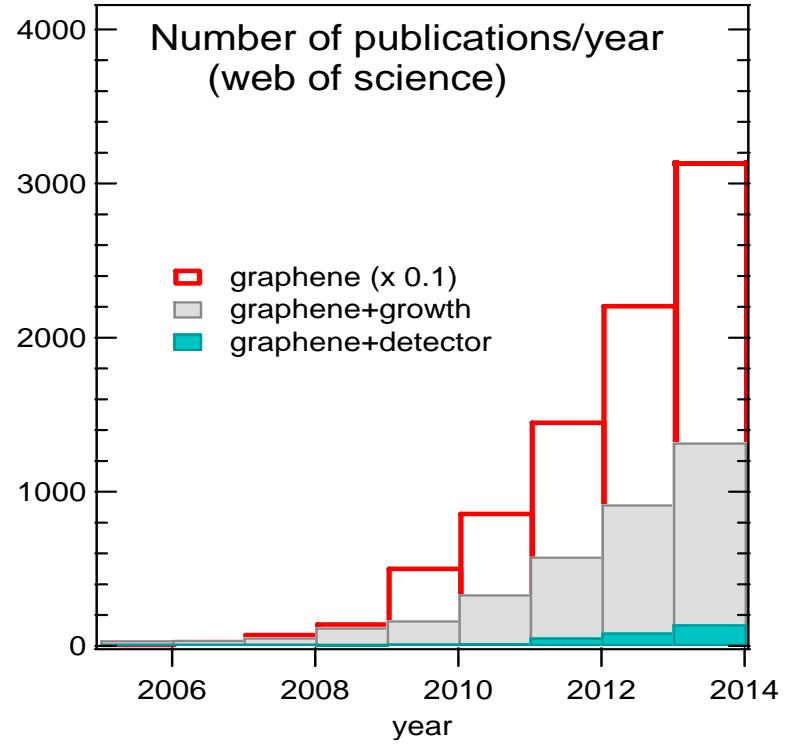
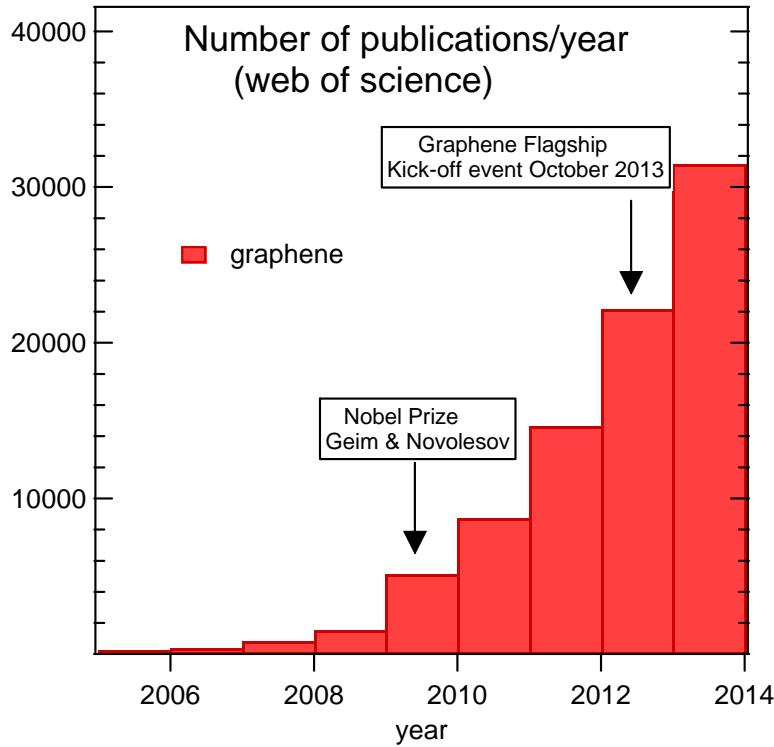
Graphene detectors

G-FET detectors: graphene as active layer; in G-FET, transient change in channel conductivity at the Dirac Point

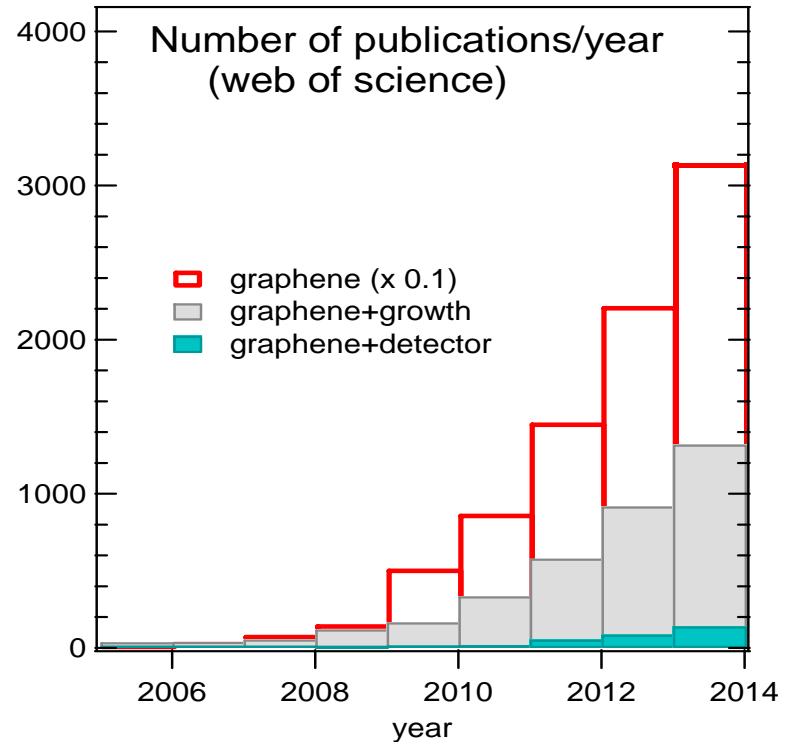
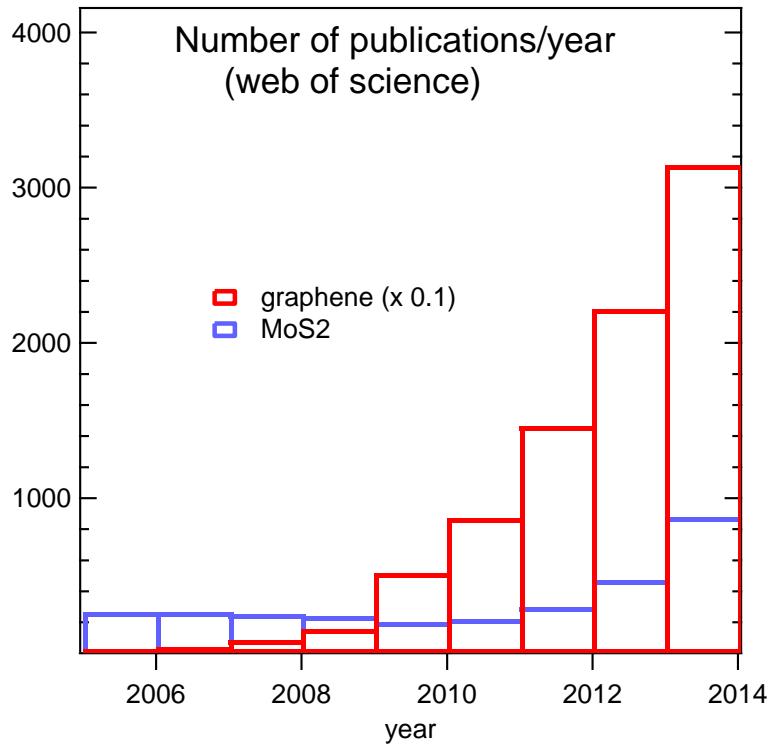


- G-FET: no charge collection; integration of graphene into robust technologies (Silicon)
- Radiation Hardness (not only for detectors): high chemical stability, demonstrated low secondary electron yield (Accelerator Physics)

State of the art and competitiveness



State of the art and competitiveness



Collaborations @ Material Science Laboratory

Ongoing collaborations

CNR-Istituto dei Sistemi Complessi, Roma

CNR-Istituto per la Microelettronica e Microsistemi, Roma

CNR-Istituto di Fotonica e Nanotecnologie, Roma

CNR-Istituto di Ricerche sulla Combustione, Napoli

Other potential collaborations

Other INFN Sections

CERN

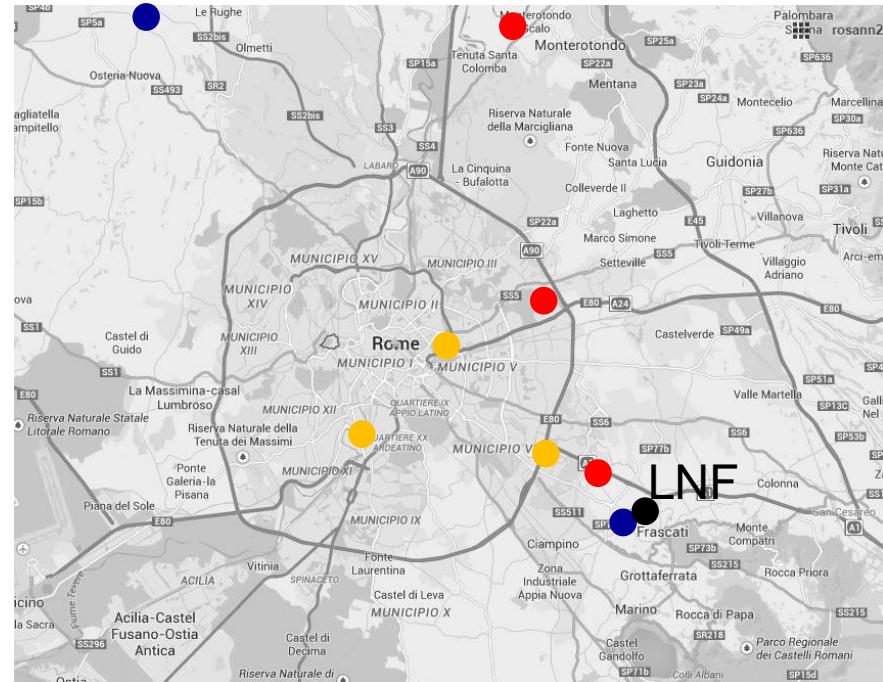
Other CNR institutes

Universities (Dip. Physics, Material Science,...)

IIT (Istituto Italiano di Tecnologia)

ENEA

FBK (Fondazione Bruno Kessler)



● CNR

● ENEA

● UNI

Critical points

Personnel

The Garfield project will expire at the end of 2015

Perspective

It is important to have a long term view to develop internal competences in the field of 2D materials.

Collaborations



LNF- INFN Frascati

Roberto Cimino

Alessandra Di Gaspare

Gianni Bencivenni



CNR- Istituto per la Microelettronica
e Microsistemi

Guglielmo Fortunato



CNR-Istituto di Fotonica e Nanotecnologie

Andrea Notargiacomo

Gabriella Castellano



Elettra Sincrotrone Trieste

Elettra Sincrotrone Trieste

Paolo Lacovig

Matteo Dalmiglio

Silvano Lizzit



Physics Department
University of Trieste

Luca Omiciuolo

Fabrizio Orlando

Alessandro Baraldi



AARHUS UNIVERSITY

Dep. Physics and Astronomy
Aarhus University , Denmark

Richard Balog

Mie Andersen

Bjarke Jørgensen

Zeljko Sljivancanin

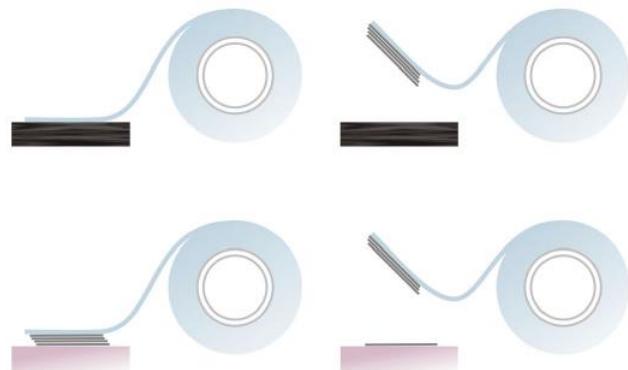
Bjørk Hammer

Liv Hornekær

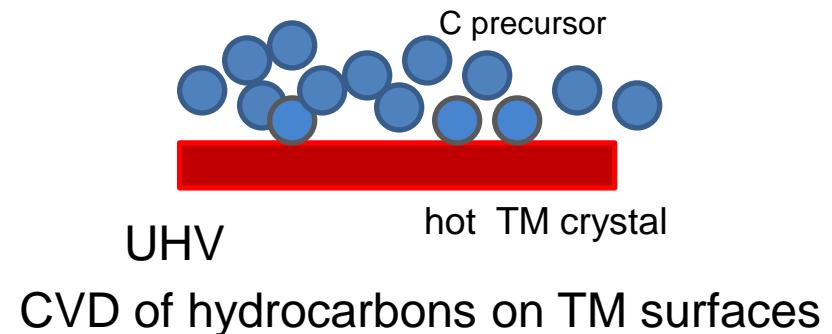
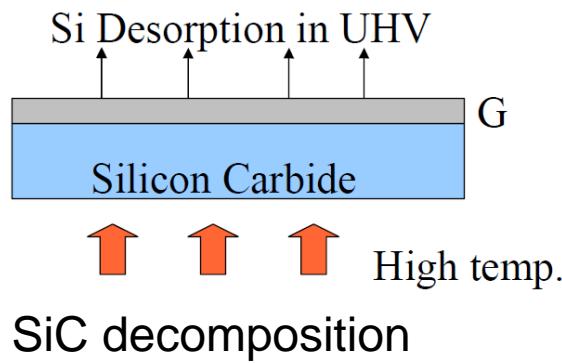
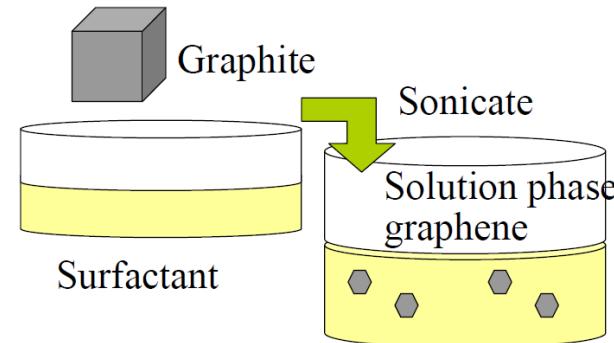
Philip Hofmann

Thanks for your attention!

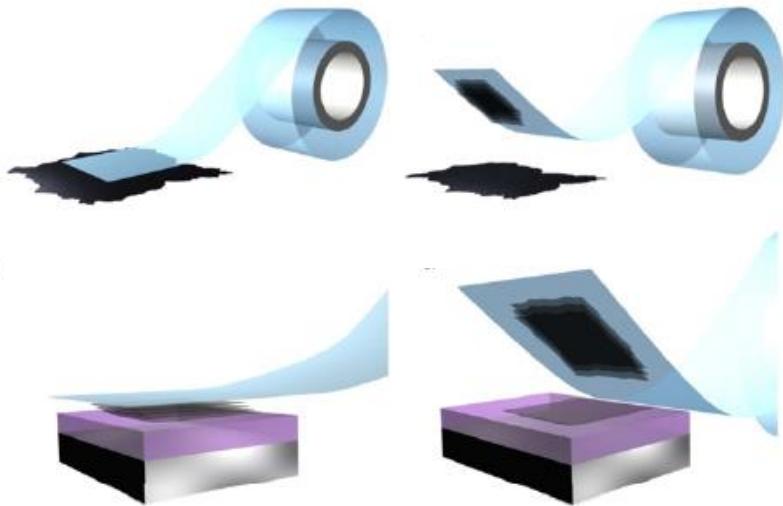
Graphene growth



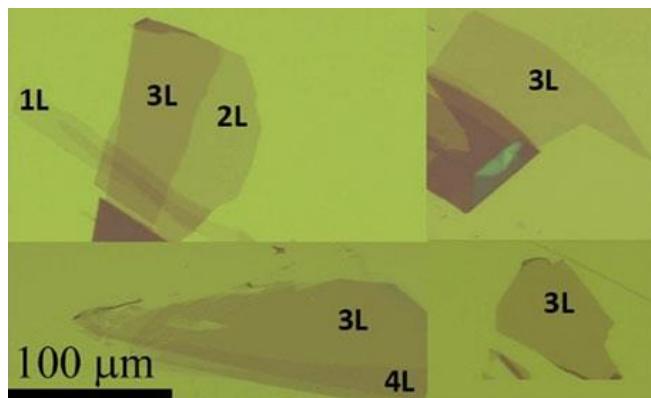
Mechanical exfoliation



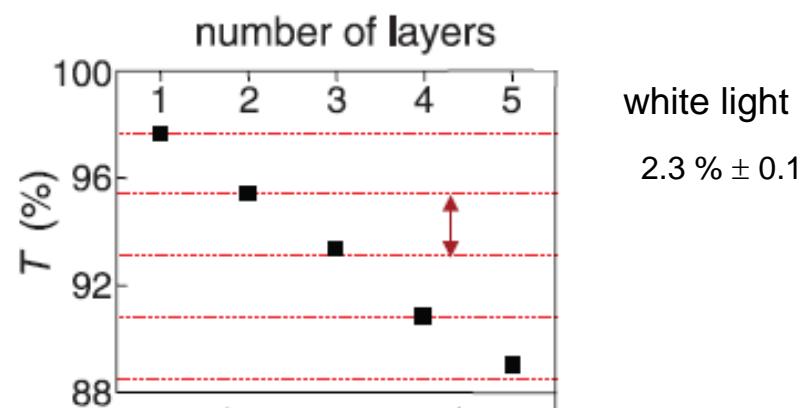
Mechanical exfoliation



Novoselov et al
Phys. Scr. T146 014006 2012



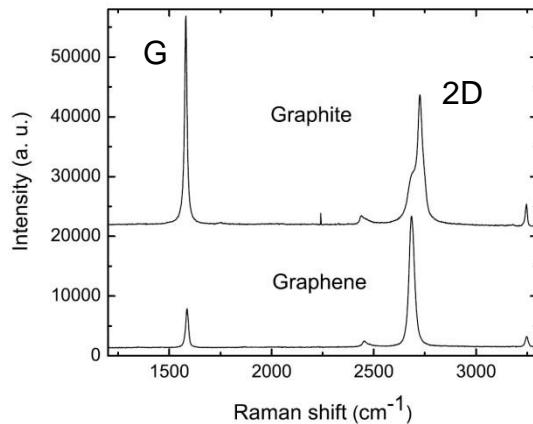
<http://emps.exeter.ac.uk/>



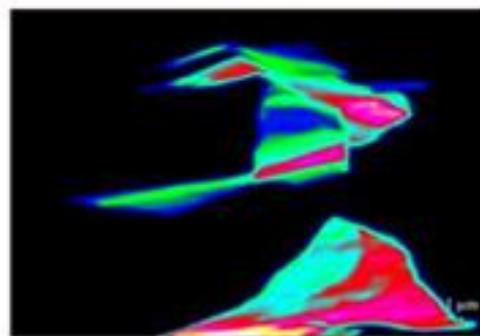
Nair et al. Science 320, 1308 2008

Production of graphene monolayers

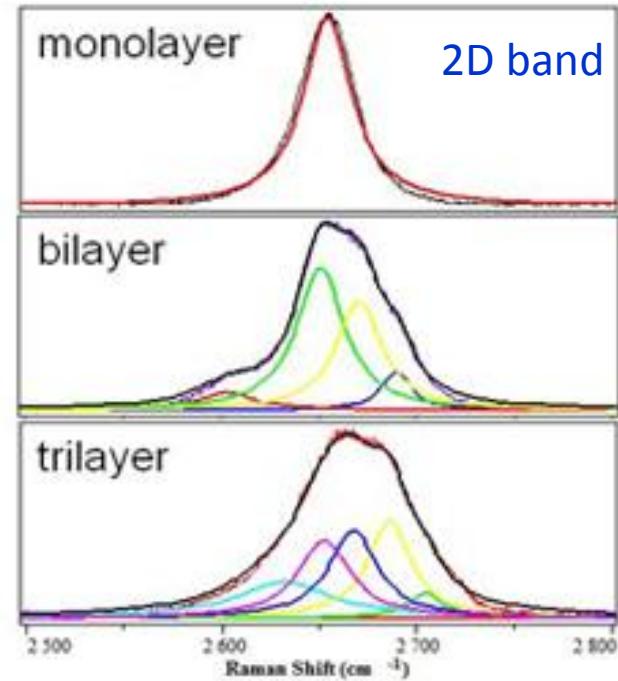
Raman spectroscopy



G band intensity Raman image



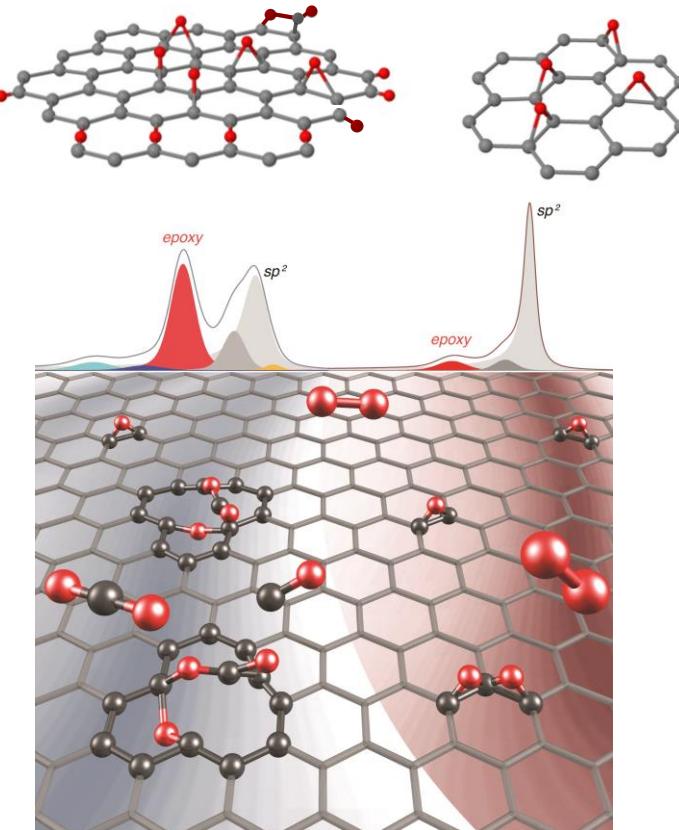
optical image



<http://www.horiba.com>

Graphene functionalization and doping

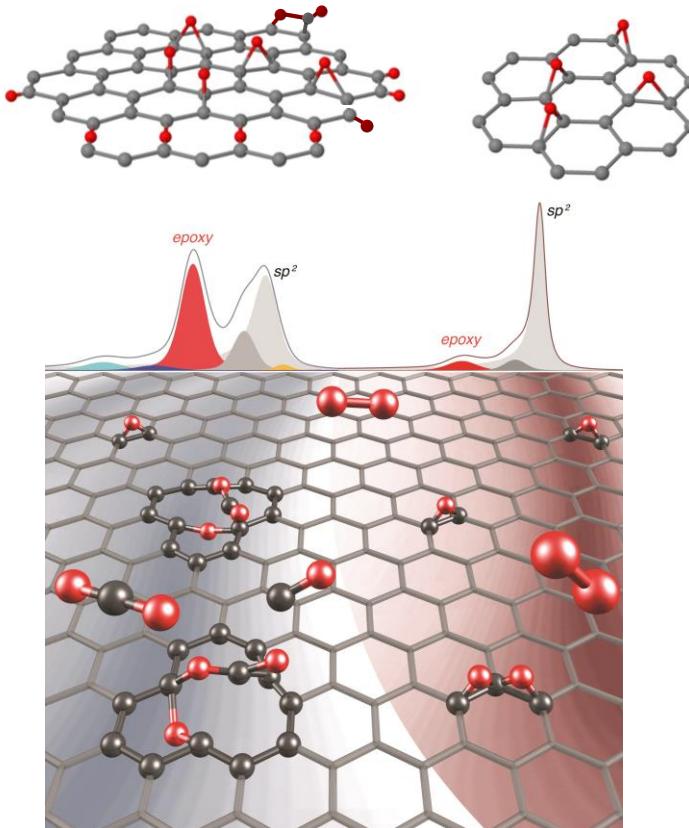
Graphene oxide



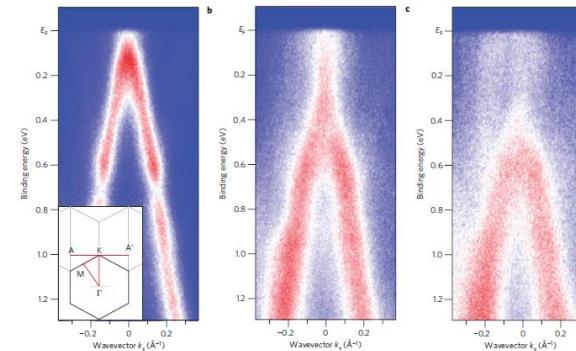
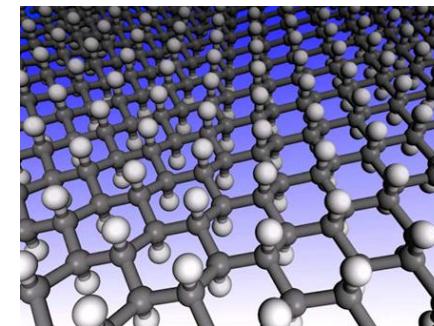
Larciprete et al. JACS 133, 17315 2011

Graphene functionalization and doping

Graphene oxide



Hydrogenated graphene GRAPHANE

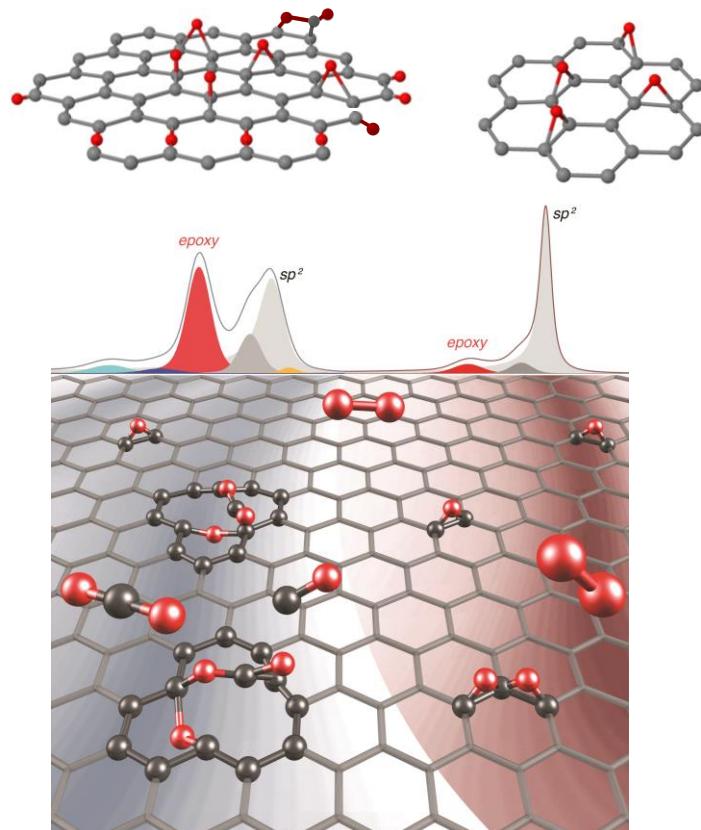


Balog et al. Nature mat. 9 (2010) 315

Larciprete et al. JACS 133, 17315 2011

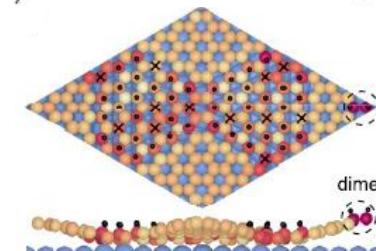
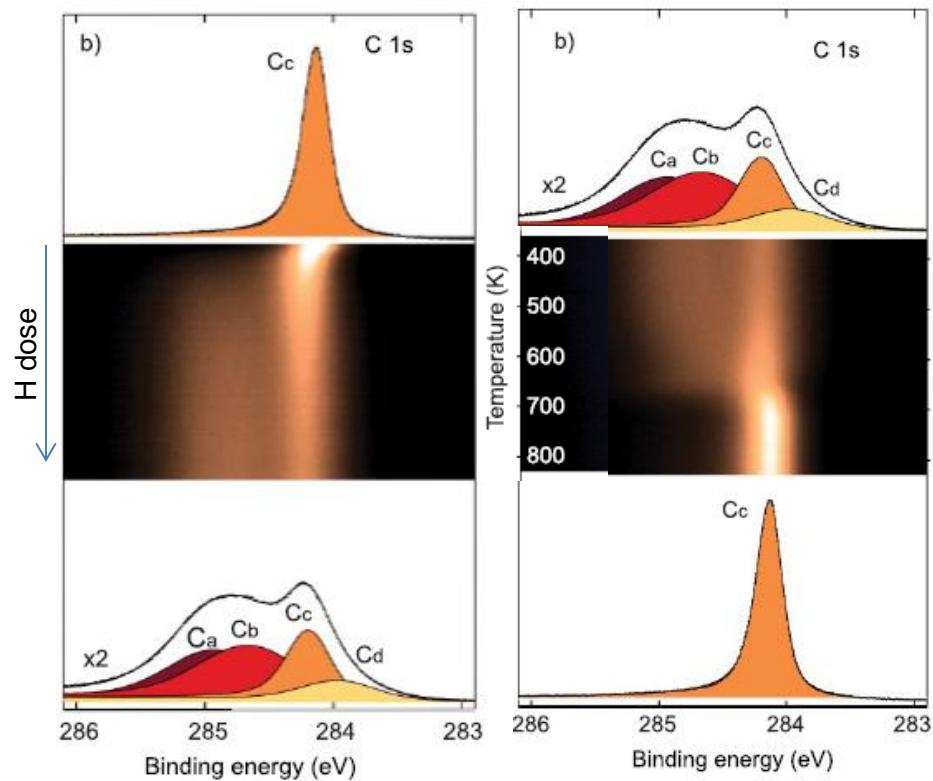
Graphene functionalization and doping

Graphene oxide



Larciprete et al. JACS 133, 17315 2011

Hydrogenated graphene GRAPHANE



Balog, RL, et al. ACS Nano 7 (2013) 3823