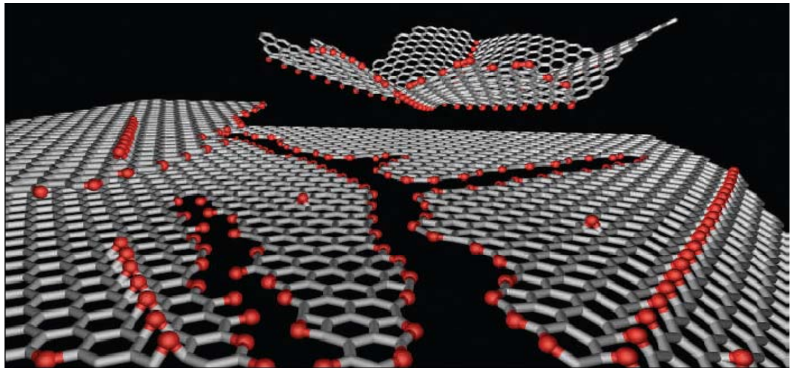
CHEMICALLY DERIVED GRAPHENE: **ELECTRONIC** AND MECHANICAL PROPERTIES



Cristina Gómez-Navarro

Universidad Autónoma de Madrid

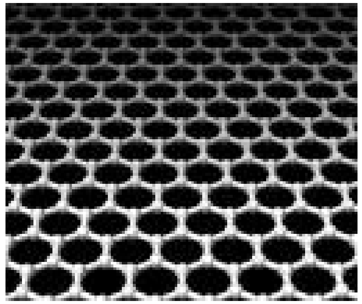
Max-Planck-Institute for Solid State Research

UNIVERSIDAD AUTONOMA DE MADRID

MAX-PLANCK-GESELLSCHAFT

Why Graphene?

Single layer of graphite



Extraordinary properties

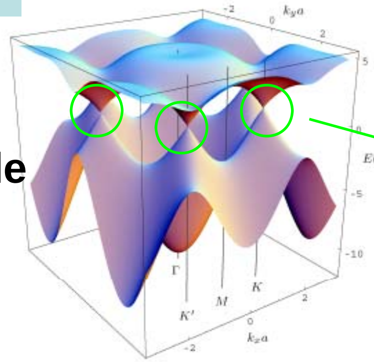
•One atom thick: real 2D material

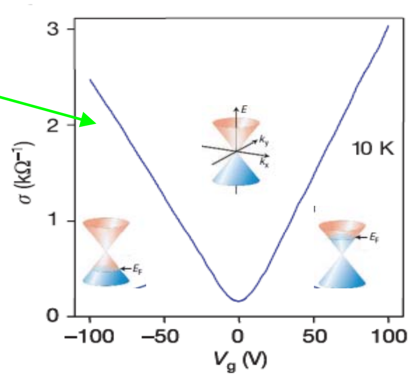
•Electronic band structure, transport properties

Semi-metal with field effect

High quality: Ballistic transport on micron scale

μ~100.000 cm²/Vs

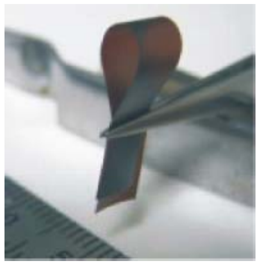




•Mechanical properties

High strength of carbon-carbon bond

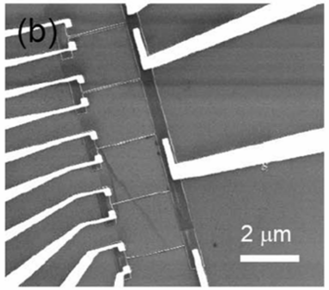
2D flexible but stiff films



Applications: Proof of concept devices

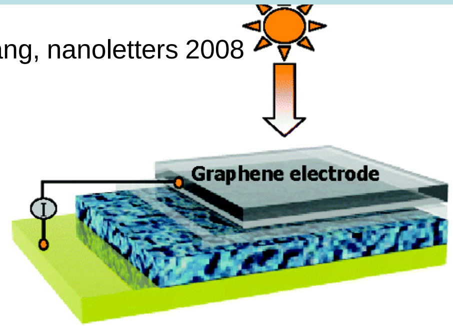
FET: graphene ribbons

Han, PRL 2007



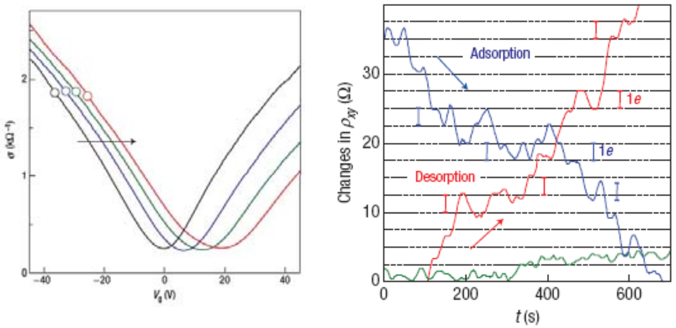
Transparent electrodes

Wang, nanoletters 2008



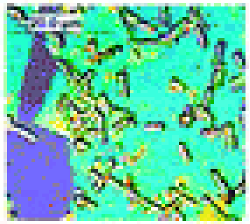
Gas sensors

Schein, Nature Materials 2007

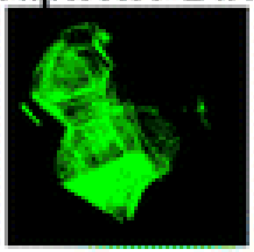


Bio devices

Mohanty, nanoletters 2008



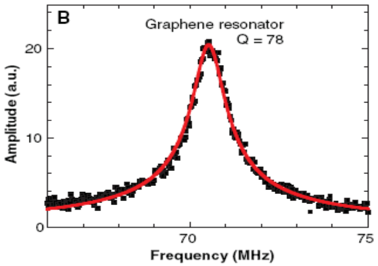
Graphene Bacte

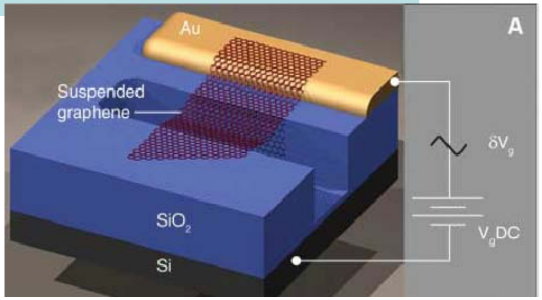


Graphene DNA

NEMS: Electromechanical Resonators

Bunch, Science 2007



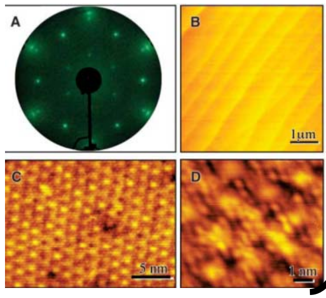


Current ways to obtain Graphene

- **Mechanical exfoliation of graphite.**
  - Very simple method, but:
    - High multilayer/monlayer ratio.
    - Finding monolayers time consuming

Novoselov et al **Nature**, 2005

- **Epitaxial growth on silicon carbide and metals**
  - Limited to certain substrates
  - Uniformity, size domain?
  - UHV, high temperatures



Berger, et al **Science**, 2006
Land, **Surface Science**, 1992

Not applicable to technology yet

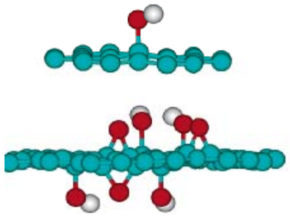
- **Chemical approach:**
- Via graphite oxide: Graphite oxide, easily layered
  - Mainly monolayers
  - Solution based
  - Reducing graphite oxide on surface?

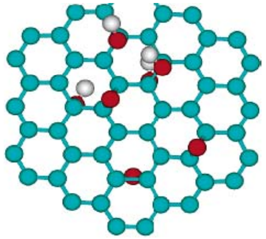
Stanovich et al **Nature** , 2006

Inexpensive, scalable, substrates

Initial idea

1st: Synthesizing graphite oxide

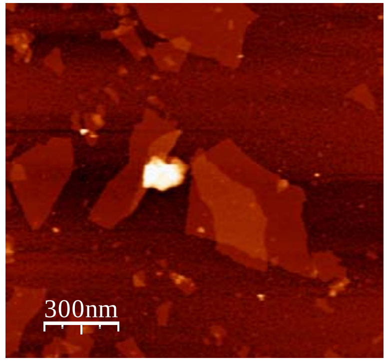




Graphite oxide: graphite functionalized with epoxy C-O-C and hydroxyl C-OH groups in the interlayer and C-OH -COOH groups at the edges of the graphene sheets.

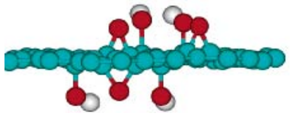
Graphite oxide layers are easy to separate in water…leading to "graphene oxide"

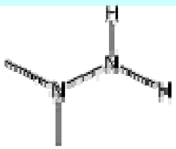
Solution process



2nd: Adsorption of single GO layers on surface

3rd: Reducing GO by chemical procedures on surface



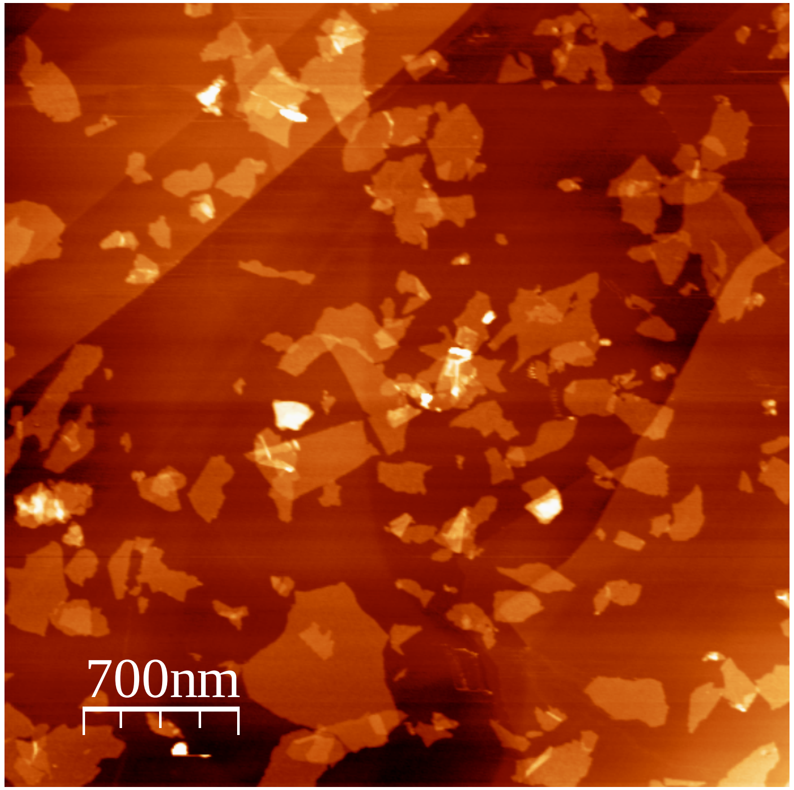


Hydrazine or hydrogen plasma

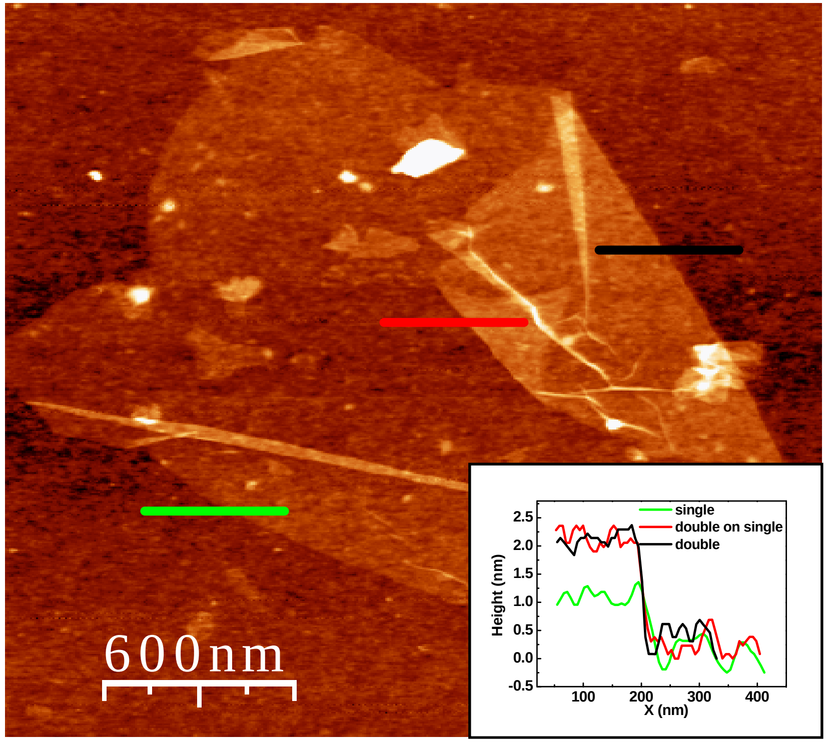
Quality and properties of graphene obtained trough this route?

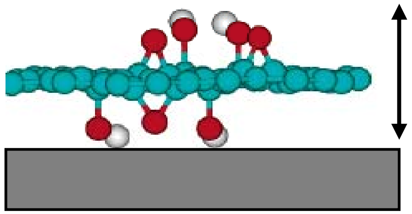
Schniepp et al J Phys. Chem. B, 110, 8535, 2006

AFM imaging of GO



Very high mono\multilayer ratio



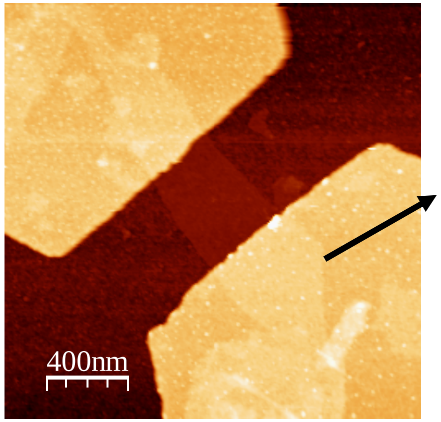


1 st layer h~ 1.0±0,1nm

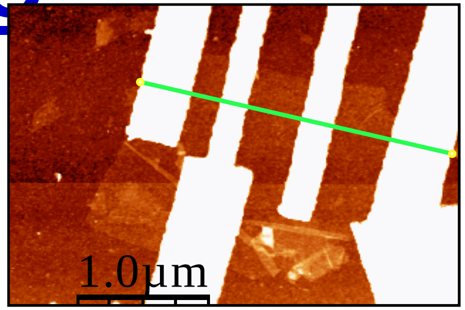
2nd layer h ~ 0,8±0,1nm

h in agreement with theoretical expectation

Electronic transport GO



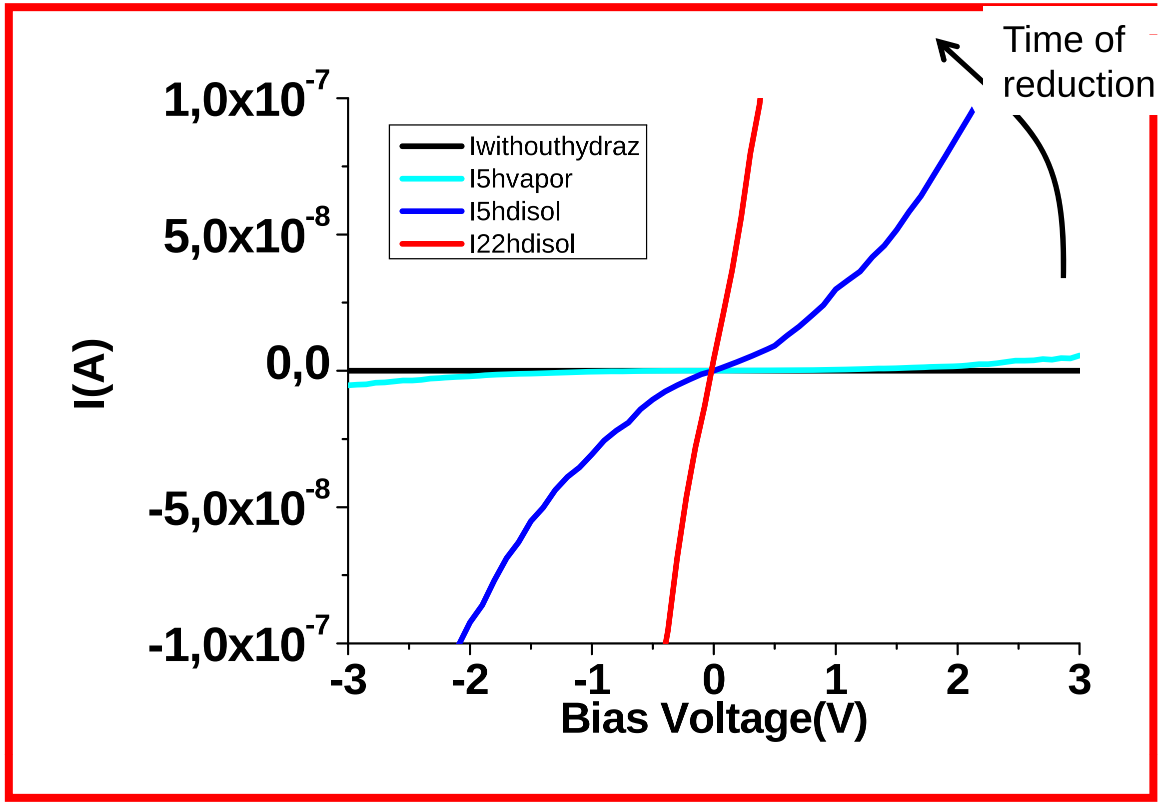
Electrodes by e-beam lithography



IV curves as a function of reduction time with hydrazine

Before reduction good insulator

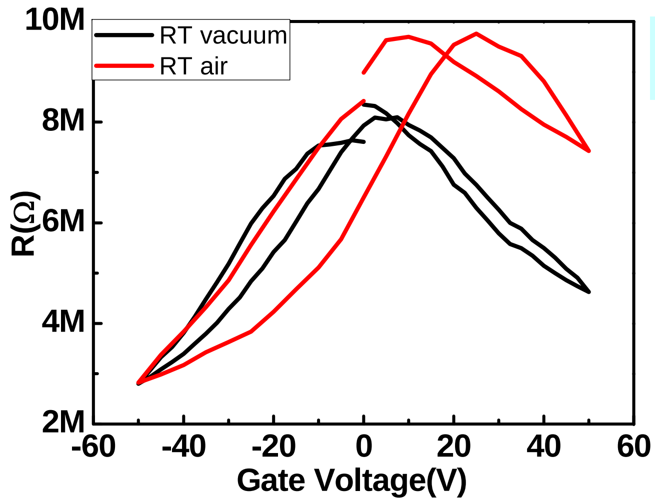
Reduction improves conductivity 3 orders of magnitude



Maximum in conductivity after 24h of NH or 5 sec H plasma

Fixed channel length

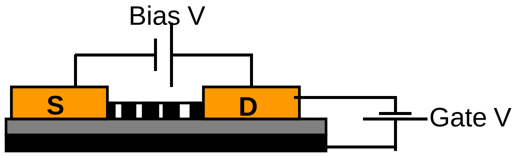
Electronic transport reduced GO



Ambipolar behaviour similar to pristine graphene

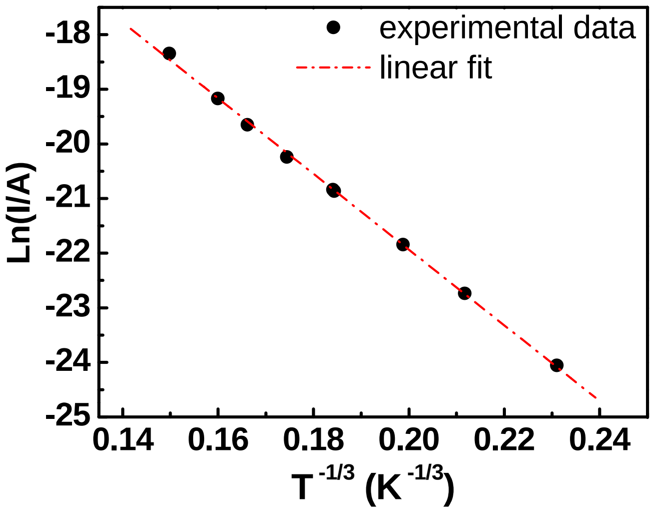
Conductivity: σ=0.1-1 S/cm

Mobility: μ=-0.1-1 cm²/Vs



$$\mu = \frac{1}{e}\frac{\sigma}{n}$$

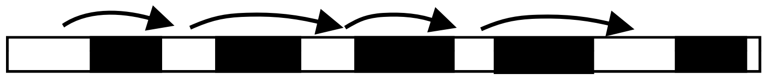
For high quality graphene μ=1.000-100.000 cm²/Vs



Temperature dependence indicates a hopping transport mechanism

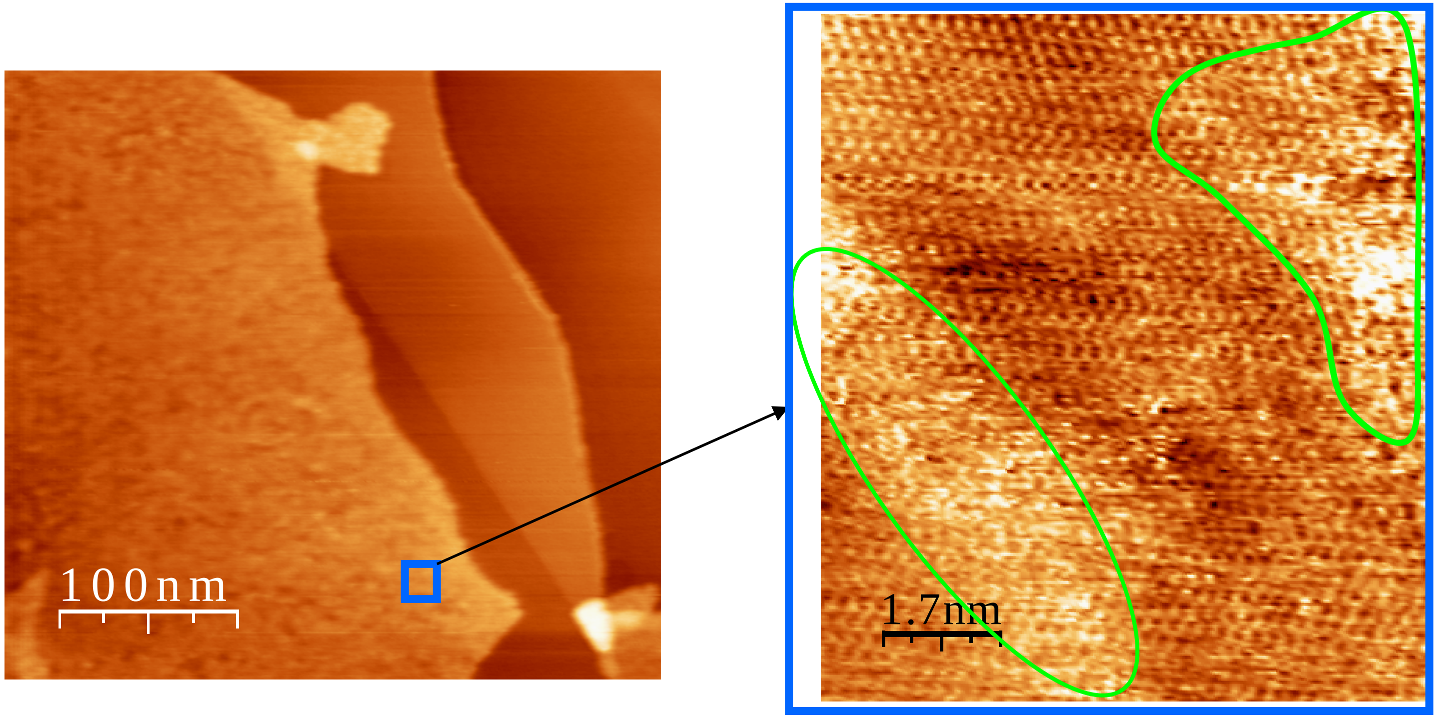
$$I = I_0 e^{\left(T_0/T\right)^{1/n}}$$

Hopping



High resolution imaging of GO

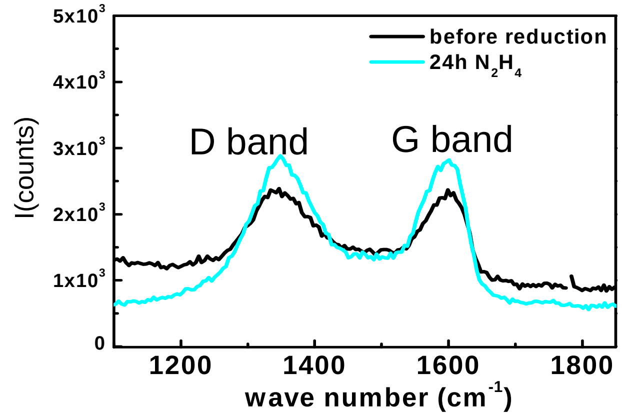
GO on HOPG



AFM: wrinkling

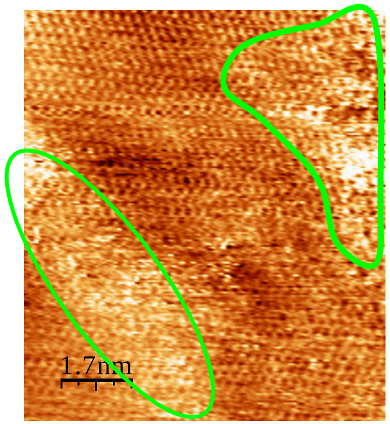
STM: ordered\disordered regions

Raman spectroscopy: GO

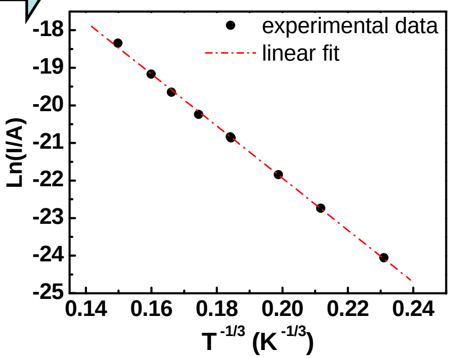


G/D ratio:
sp^2 carbon domain size of ~ 5-6 nm

Ferrari et al. *Phys Rev B* **2000**
Tuinstra et al. *J Chem Phys* **1970**

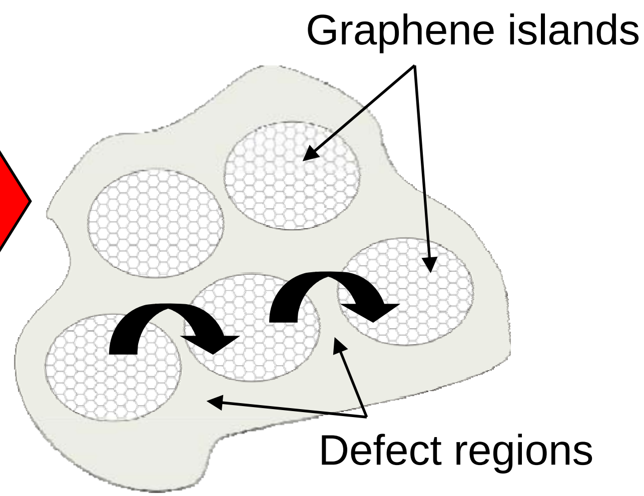


STM



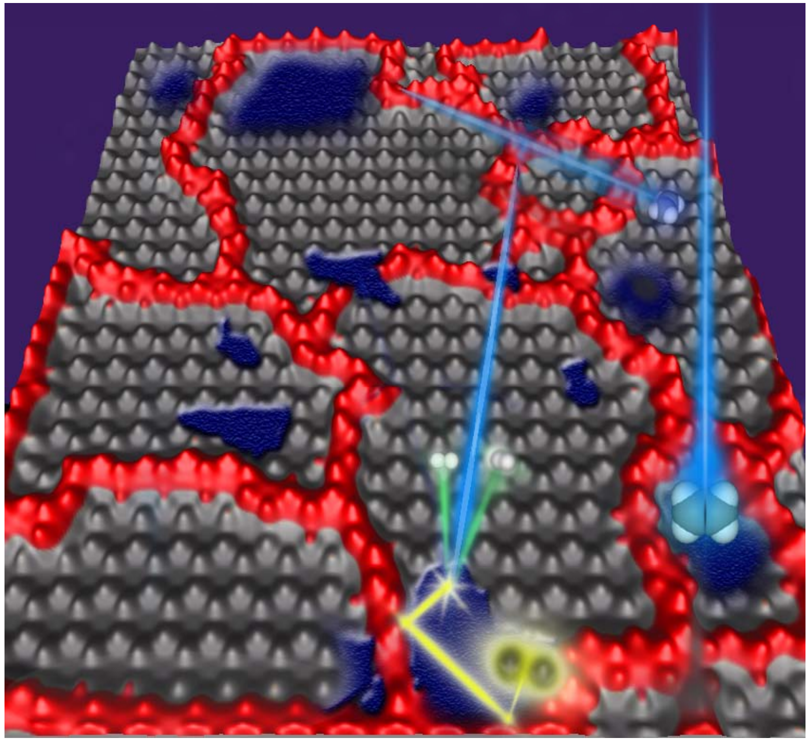
Hopping conduction

Model



Gomez-Navarro et al. *Nanoletters* **7** 3499 ***2007***

2nd step: Chemical Vapor Deposition of ethylene

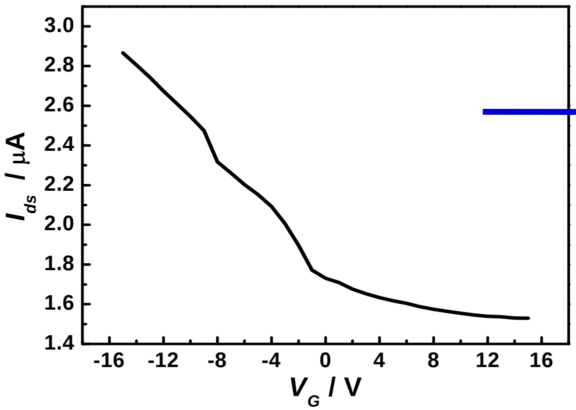


- High T
- Decomposition of C_2H_4
- obtaining atomic C
  to be incorporated in vacancies
- High T facilitates healing

Flow ethylene for 3 min at 800 ºC

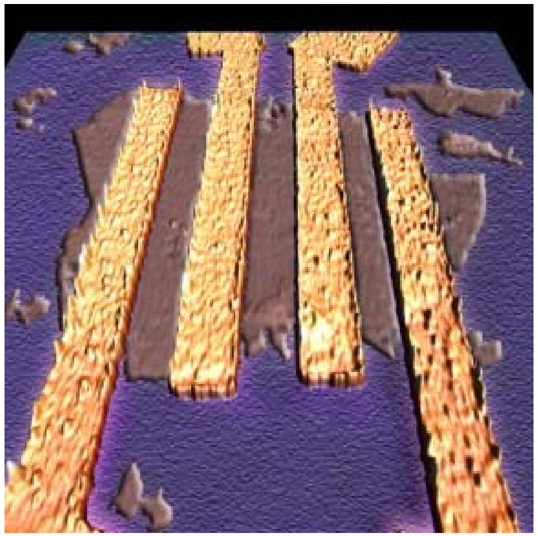
CVD treated GO: improved conductivity

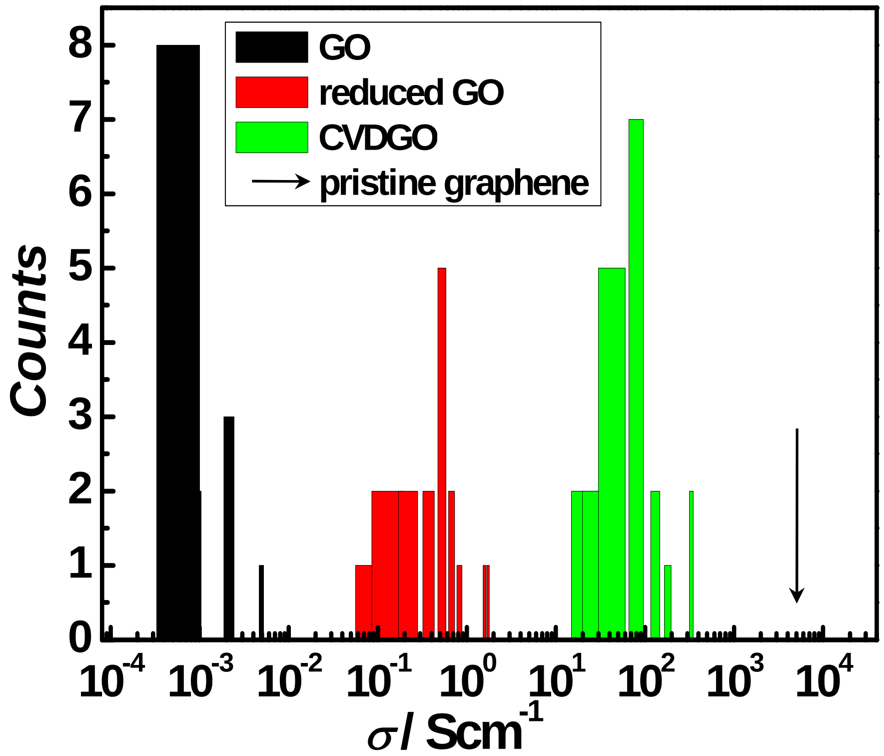
After CVD conductivity increases two orders of magnitude



Conductivity: σ=20-200 S/cm

Mobility: μ~50-100 cm²/Vs

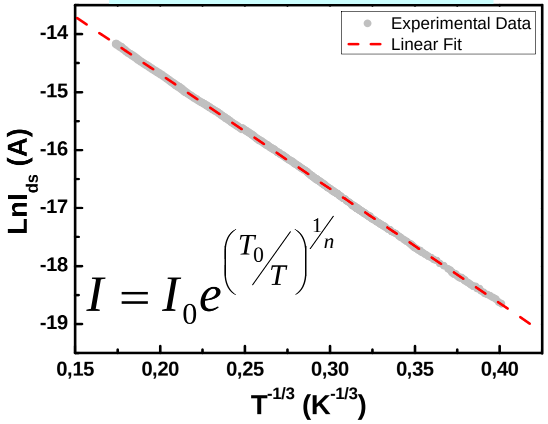




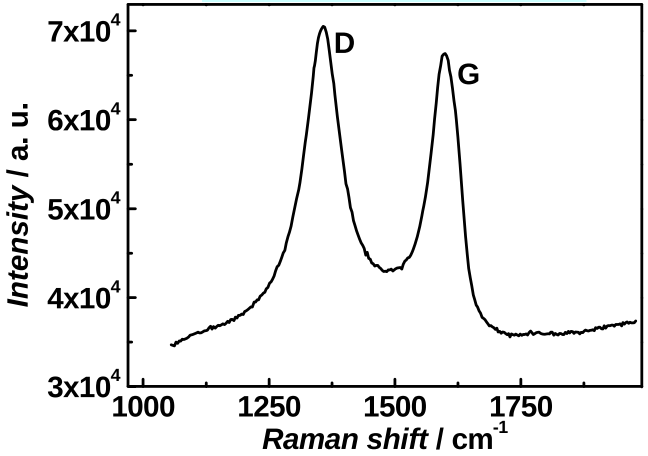
Lopez et al. *Advanced Materials*, 2009

CVD treated GO: Raman and coductivity

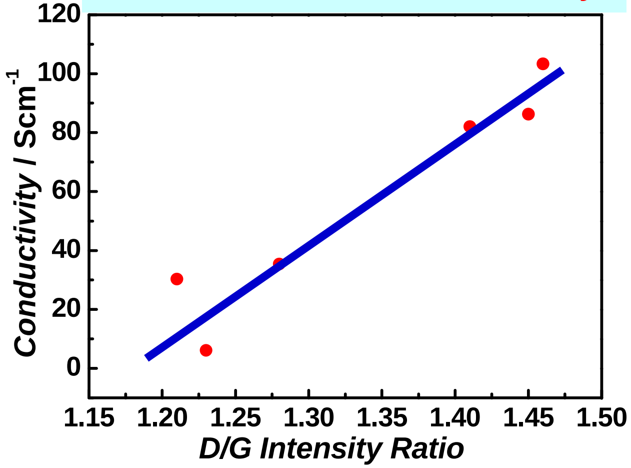
hopping transport



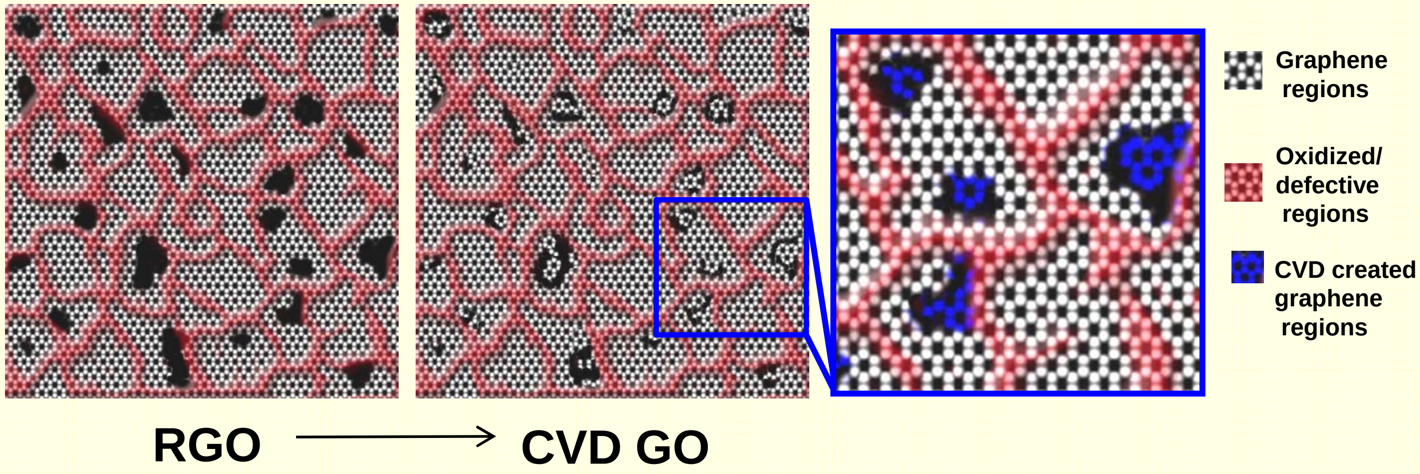
High D/G ratio



Correlation D/G conductivity

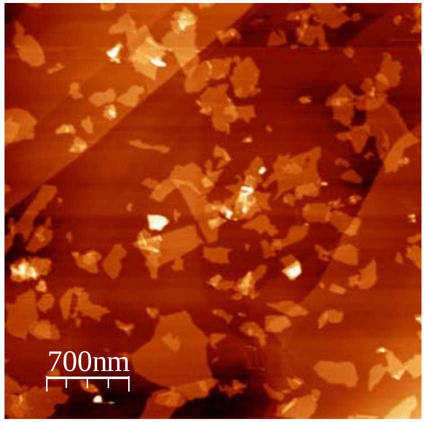


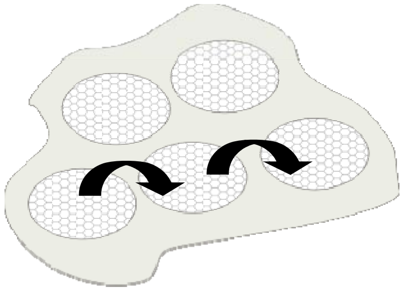
New smaller graphene regions

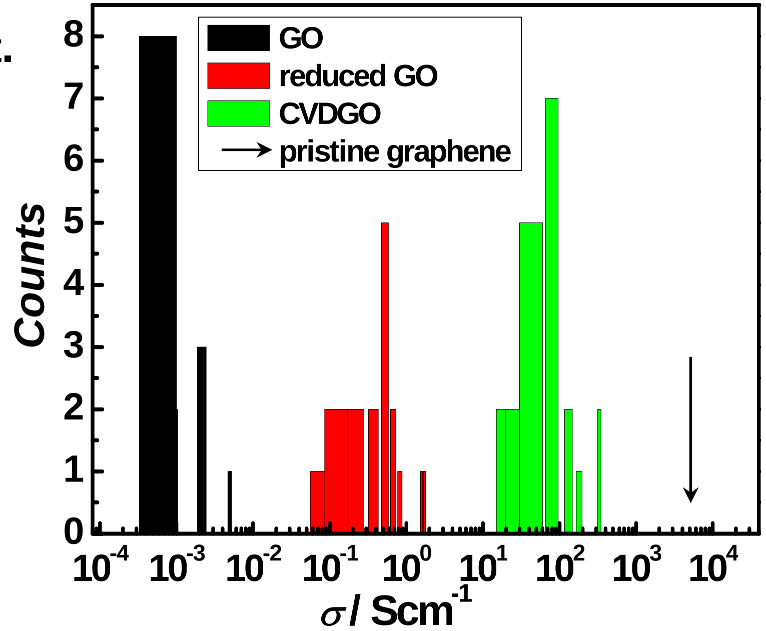


Conclusions on electrical transport

- GO routes provides access to a large scale production of graphene monolayers.
- Reduction improves conductivity in 3 orders of magnitude
- CVD of ethylene increases conductivity in 2 orders of magnitude.
- CVDGO still contains a considerable amount of defects.
- Large range of conditions for improvement.



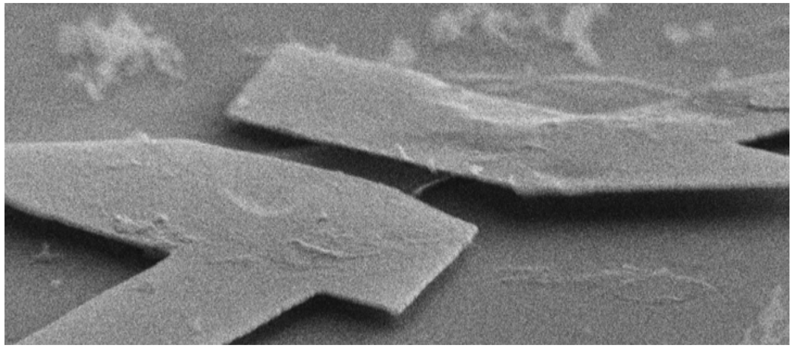


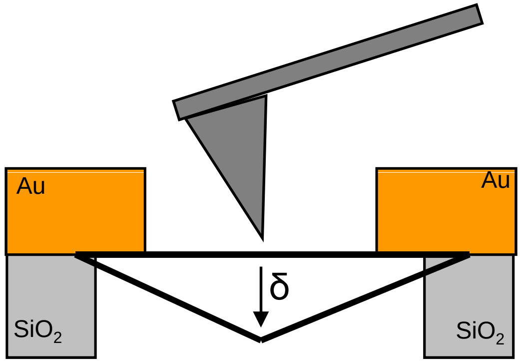


Gomez-Navarro et al. *Nanoletters* ***2007***

Lopez et al. *Advanced Materials* ***2009***

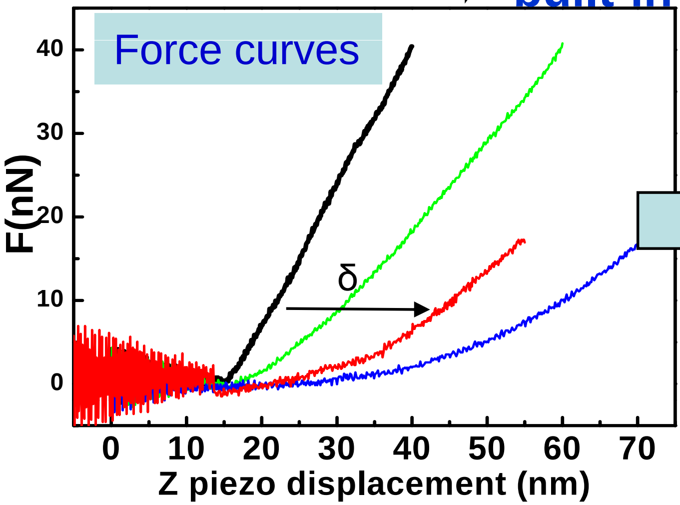
GO: mechanical properties





$$K_{eff} = 32Ew(t/l)^3 + 17T/l$$

Force Constant → **Young modulus, built-in tensions**

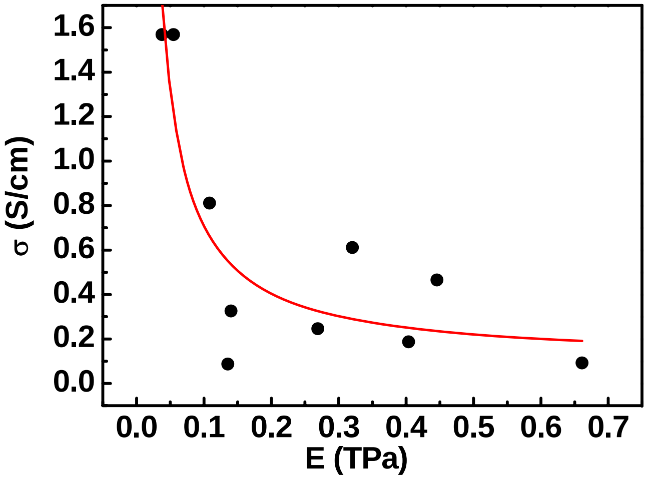


K_1, K_2, K_3…

E=0.3 TPa

T=4 nN

Correlation between conductivity and elastic modulus



Gomez-Navarro et al. *Nanoletters* ***2008***

Acknowledgments

Max-Planck-Institut fuer Festkoerperforschung

- **Klaus Kern**
- **Marko Burghard**
- **Thomas Weitz**
- **Ravi Sundaram**
- **Alexander Bittner**

Universidad Autonoma de Madrid

- **Vicente Lopez**
- **David Olea**
- **Felix Zamora**
- **Julio Gomez Herrero**

University of Siegen

- **Matteo Scolari**
- **Alf Mews**

Nanotec Electronica

Thank you for your attention!