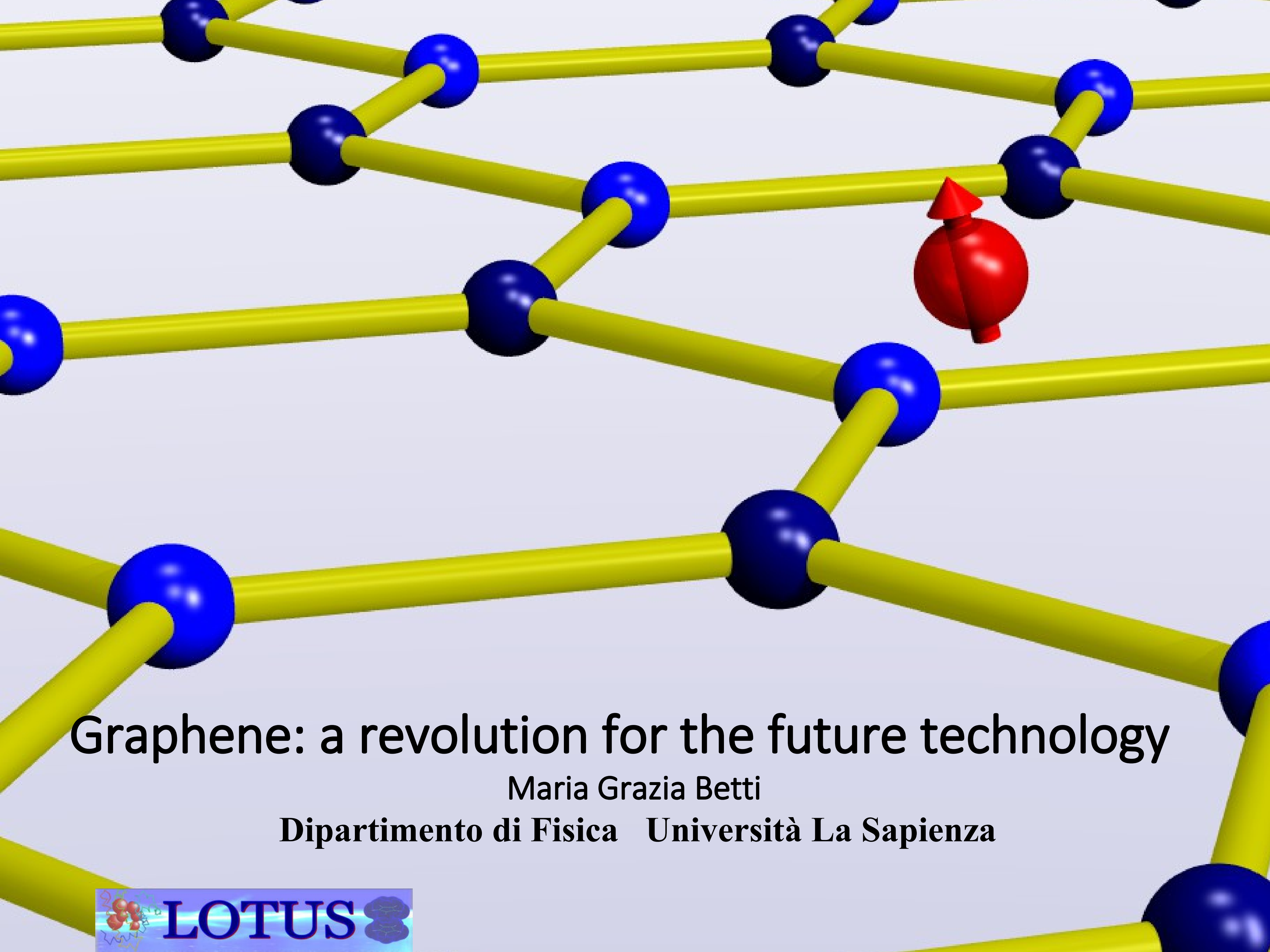
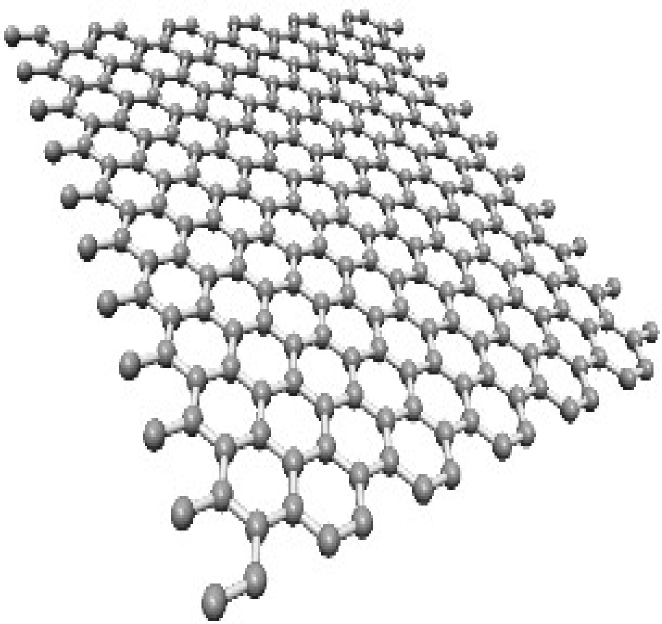


Graphene: a revolution for the future technology

Maria Grazia Betti

Dipartimento di Fisica Università La Sapienza

Outline



1- Graphene: a single layer of carbon atoms

2- Why graphene can be a revolution for future technology?

3- The roadmap of the graphene flagship

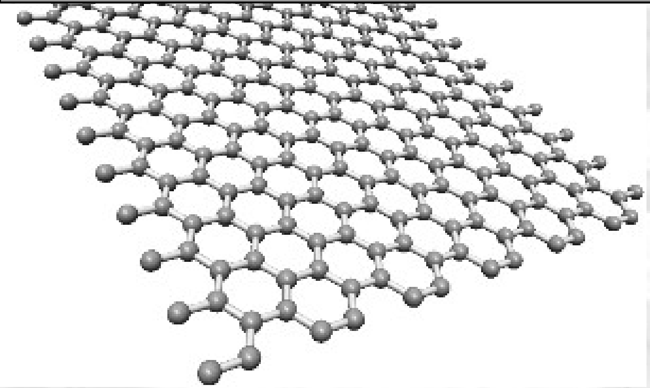
4-Graphene for the future technology:few examples

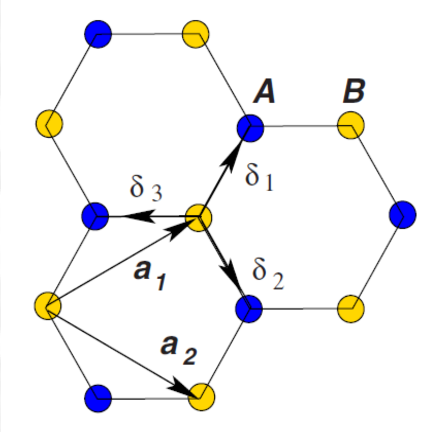
5-Is it easy to grow graphene?

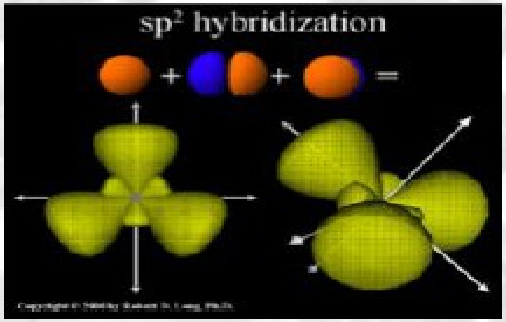
6-How to control and design the graphene properties?

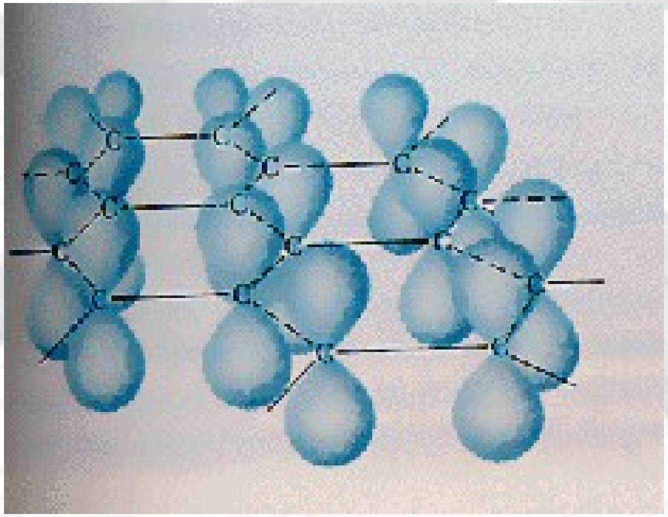
7-Three examples:
  - i) graphene: metal or semiconductor?
  - ii) graphene a buffer layer for spintronics
  - iii) graphene for energy storage and Li batteries

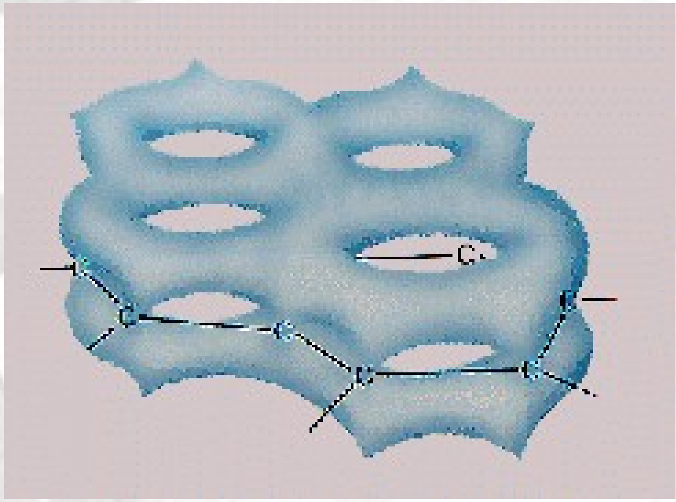
Graphene: a single layer of carbon atoms





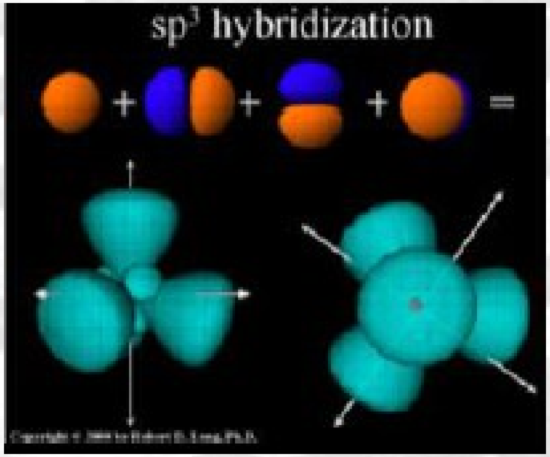


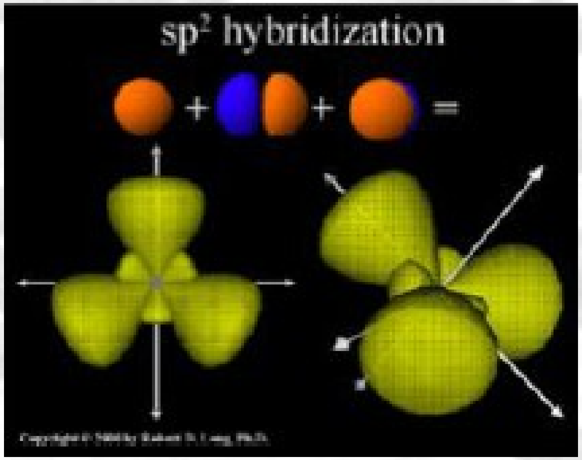


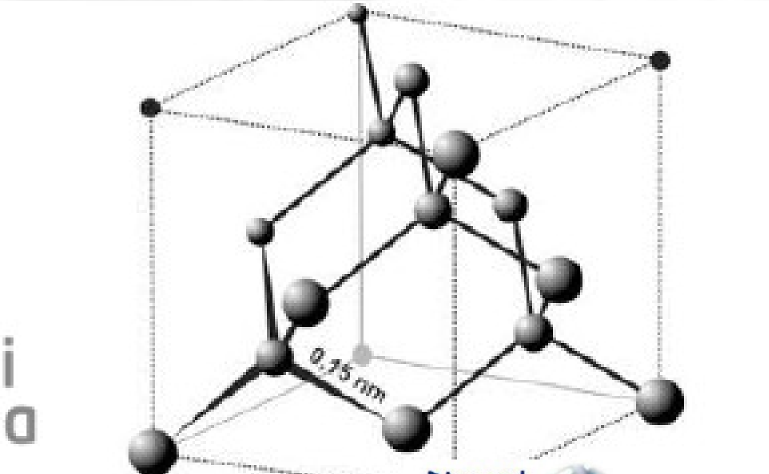


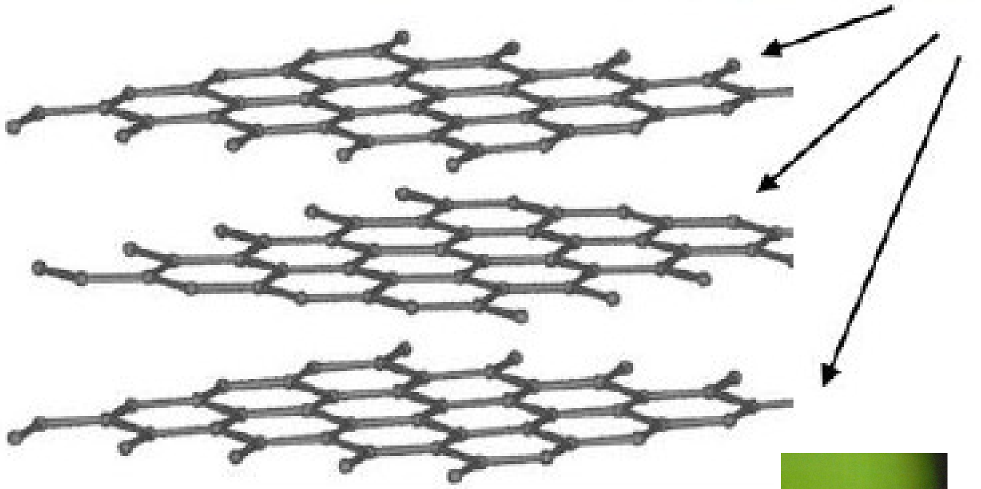
3 electrons to bind to other 3 atoms and keep one to share with everybody:
METALLIC STATE and GOOD CONDUCTOR IN THE PLANE

Hybridization of carbon atoms









Insulator

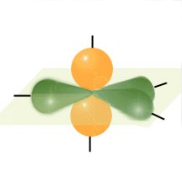
SemiMetal

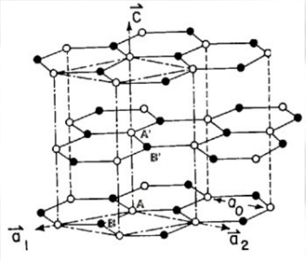
Carbon: 0D, 1D, 2D and 3D configurations

3D

Graphite

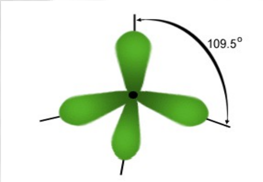
Semimetal

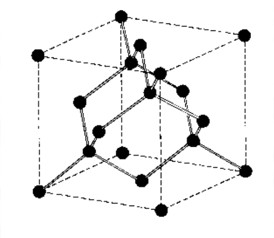




Diamond

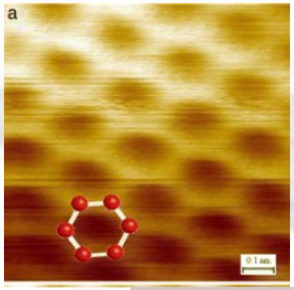
Insulator

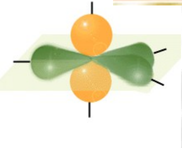


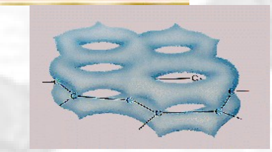


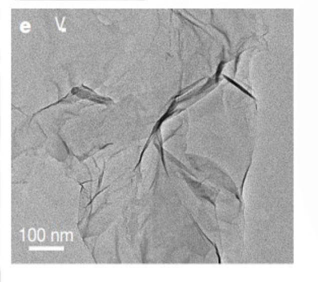
2D

Graphene





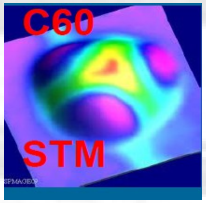


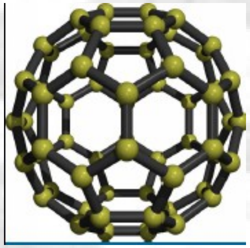


Novoselov, Geim 2004
Nobel prize 2010

0D

Fullerenes

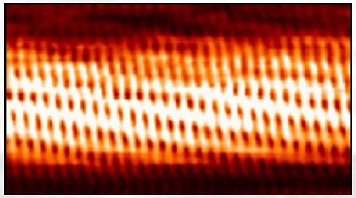


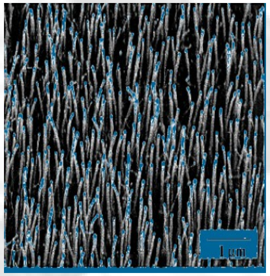


C_{60} *Curl, Kroto, Smalley 1985*
Nobel prize 1996

1D

Carbon Nanotubes



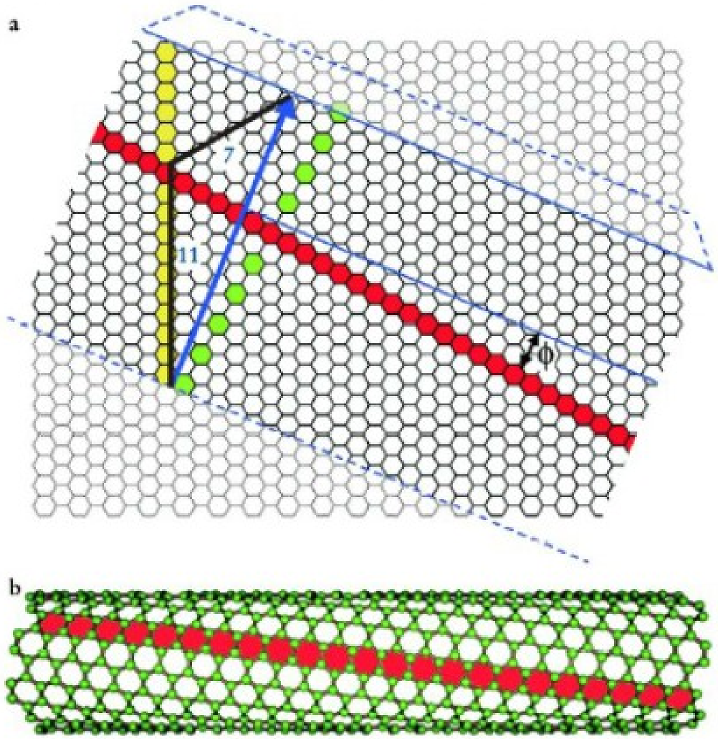


Multi-wall 1991
Single-wall 1993

Metal or semiconductor

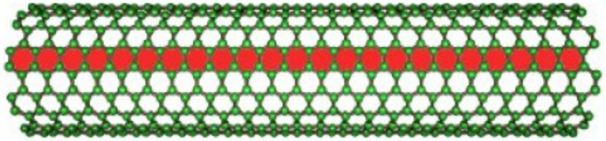
Carbon nanotubes: metallic or insulator?

Wrapping can be done along many directions in the sheet



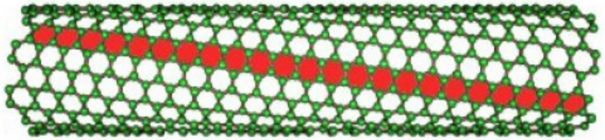
=> chiral nanotubes

Nonchiral ('armchair') nanotube



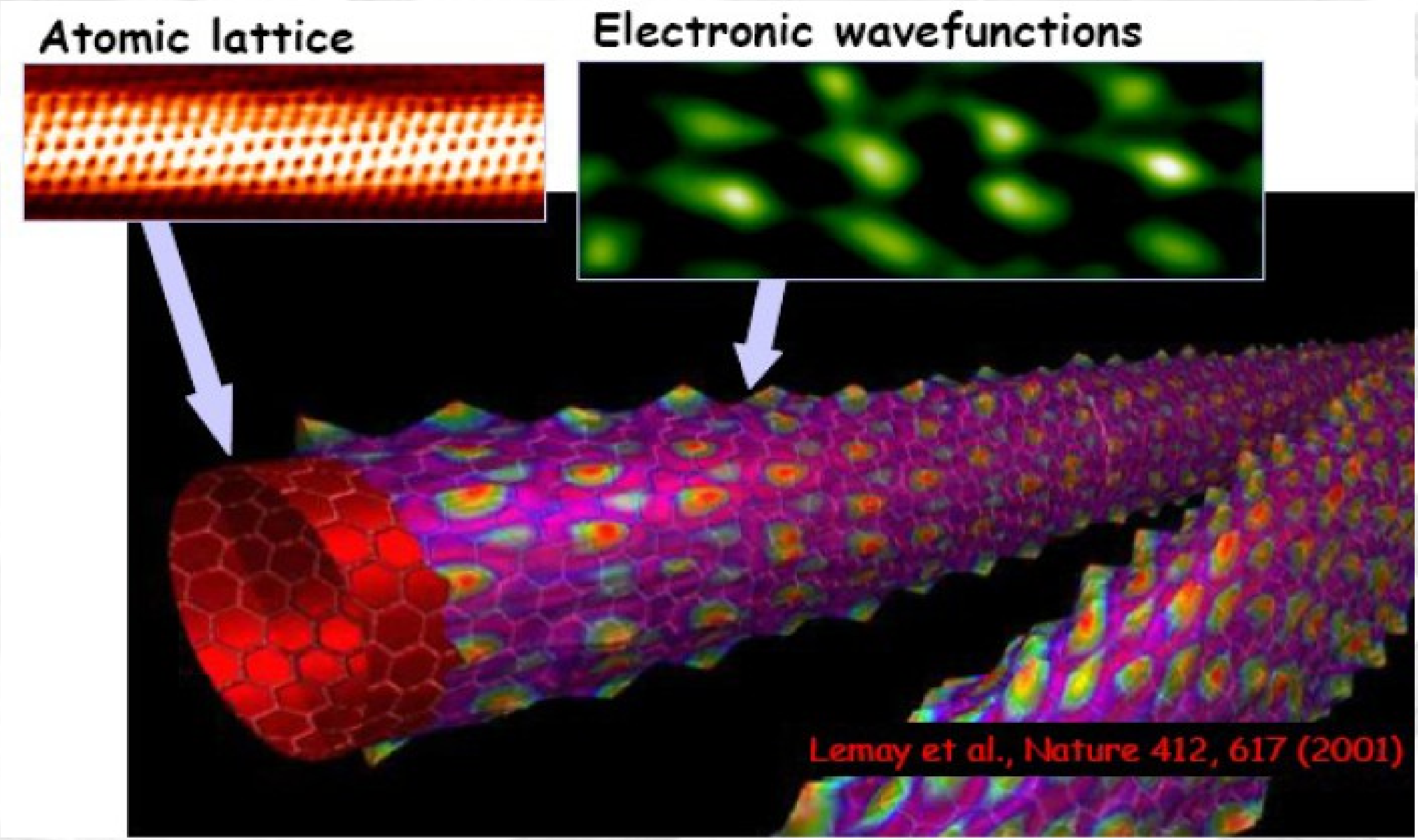
metallic

Chiral nanotube



semiconducting *or* metallic

Carbon nanotubes: metallic or insulator?



Lemay et al., Nature 412, 617 (2001)

Why graphene for the future technology?

1- High Electrical conductivity

Sheet conductivity of a 2D material

$$\sigma = en\mu$$

The mobility is μ=15.000*-200,000 cm^{2}/Vs

with a carrier density of $n=10^{12}$ cm^{-2}.

2D sheet resistivity = 31 Ω

The resistivity is dominated by impurity scattering (independet from temperture 10-100K) and limited by acoustic phonons scattering

*Geim Novoselov Nat. Mat (2007) **6,** 183

2- High Thermal conductivity

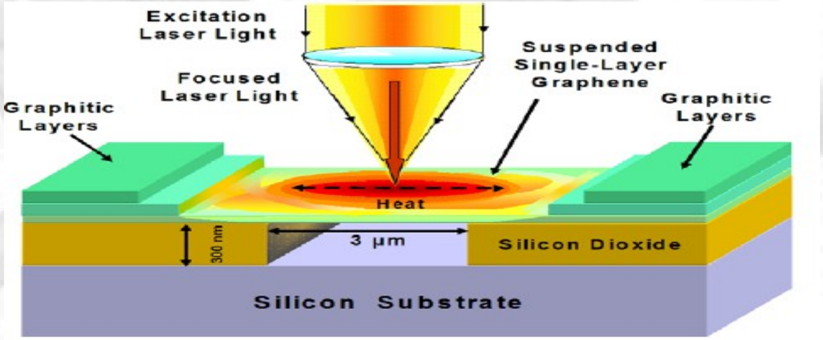
Thermal conductivity of graphene is

1500-5300 W/m K*

Copper thermal conductivity is

401 W/mK.

* Balandin et al Nanoletters 8 902 (2009)



A.A. Balandin, S. Ghosh, W. Bao, I. Calizo, D. Teweldebrhan, F. Miao and C.N. Lau, *Nano Letters*, **8**: 902 (2008).

Why graphene for the future technology?

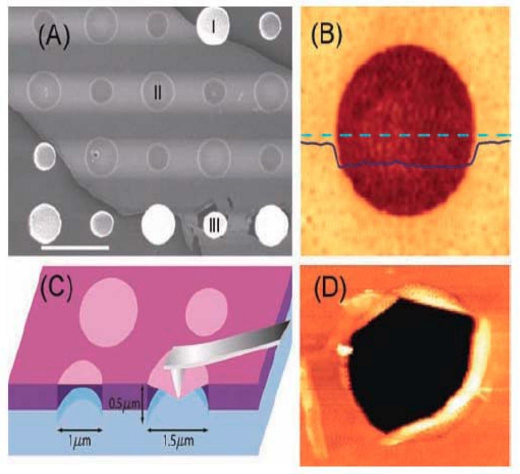
3- Mechanical strength

Graphene is the strongest material ever tested!
Tensile strength of 130GPa
and Young modulus 1TPa

The spring constant of graphene has beem measured by Atomic Force Microscope
K=-5N/m

Thus graphene is more than 100 times stronger than steel.

Mechanical strength



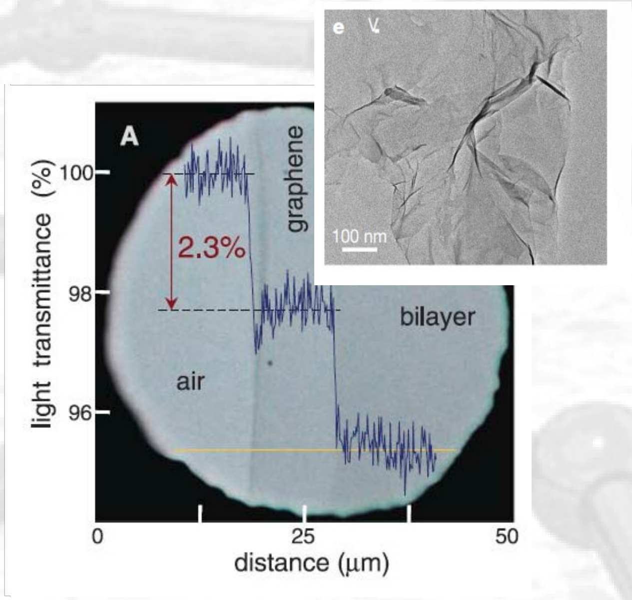
Young's modulus 1 TPa

*C. Lee et al,Science **321**, 385 (2008)*

Why graphene?

4- Trasparency

Nearly trasparent

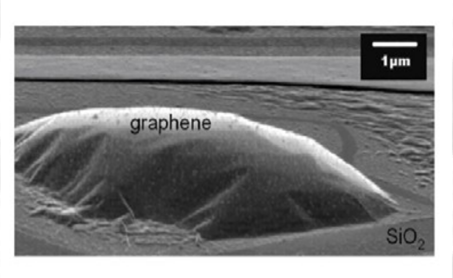


*R. R. Nair et al.Science **320**, 1308 (2008).*

Red light absorption 2.3%
R. Nair Science 320, 1308 (2008)

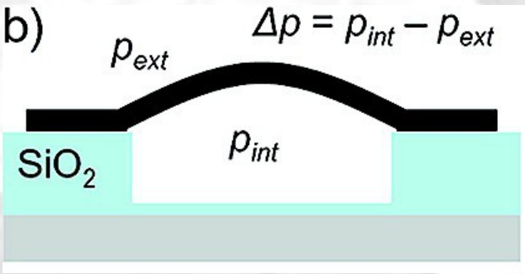
5- Impermeable

Impermeable membrane!



$$SiO_2 + 4HF \xrightarrow{water} SiF_4 + 2H_2O$$

One-atom thick impermeable membrane even to He!

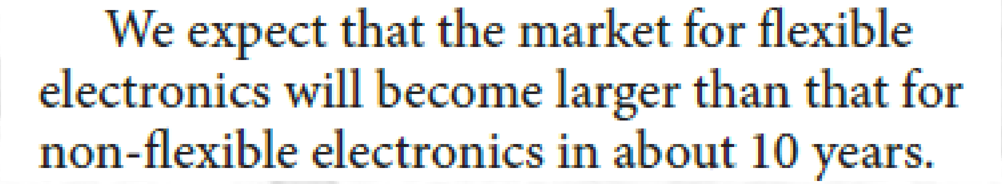


Why graphene?

2- Electrical, thermal conductivity, mechanical strength and flexibility

Graphene, on flexible substrates, is mechanically robust and has the smallest bending radius among all flexible trasparent conductors

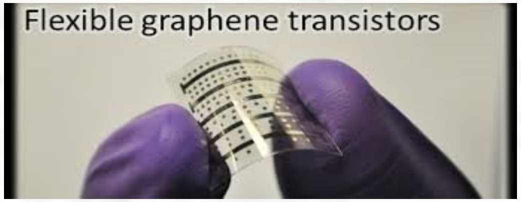
3. Bae, S. H. *et al. ACS Nano* 7, 3130–3138 (2013).



We expect that the market for flexible electronics will become larger than that for non-flexible electronics in about 10 years.

7. Ryu, J. *et al. ACS Nano* 8, 950–956 (2014).

Figure 1 | Graphene-based multi-touch screen showing excellent flexibility (left)[7] and possible applications in bendable or foldable mobile devices (right).



Flexible graphene transistors

Why graphene?

Electric ink

Figure 1 | Graphene-based multi-touch screen sho
applications in bendable or foldable mobile devic

© STUART BRADFIELD

Electrifying inks with 2D materials

Nature Nanotechnology,
9, 737 (2014)

Graphene for energy

Lithium battery

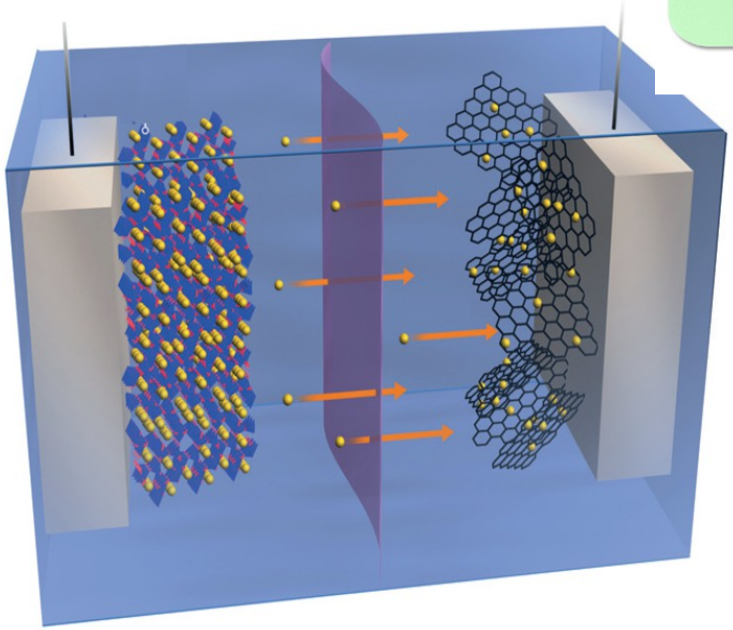
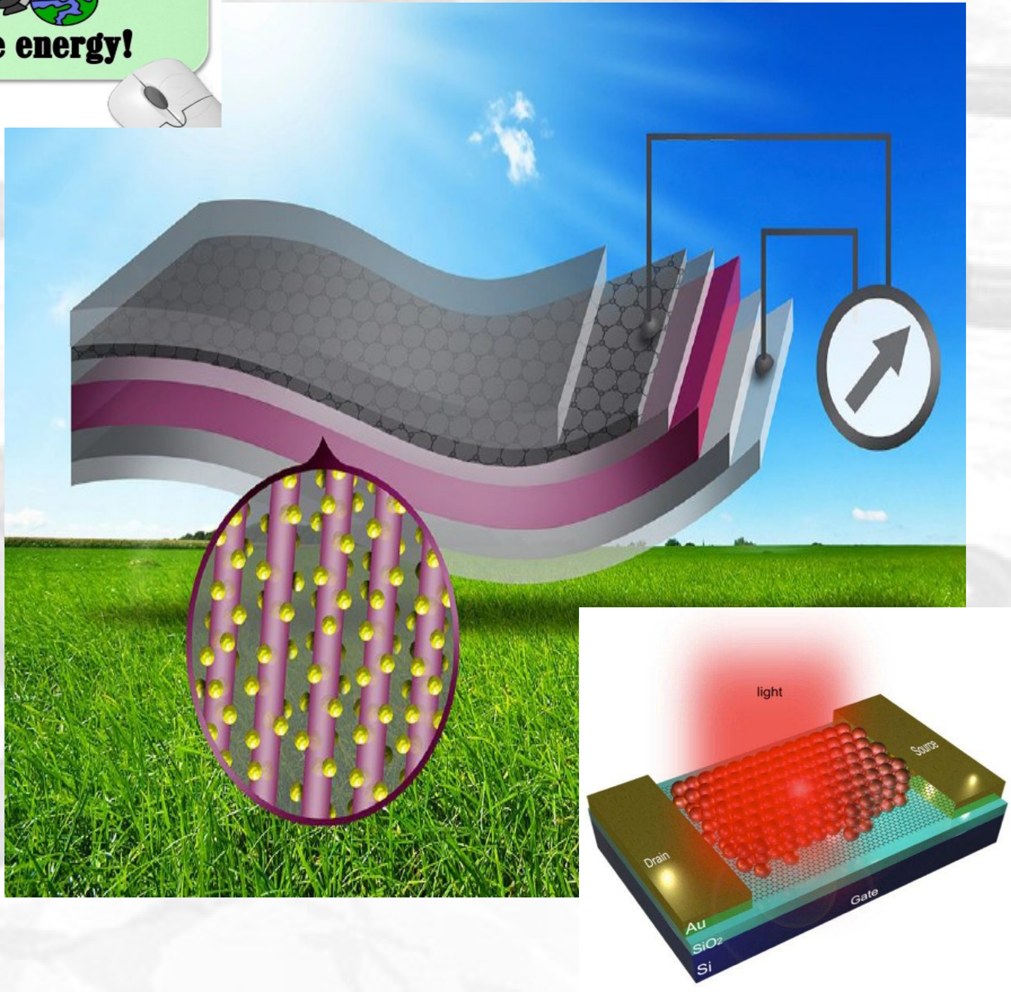
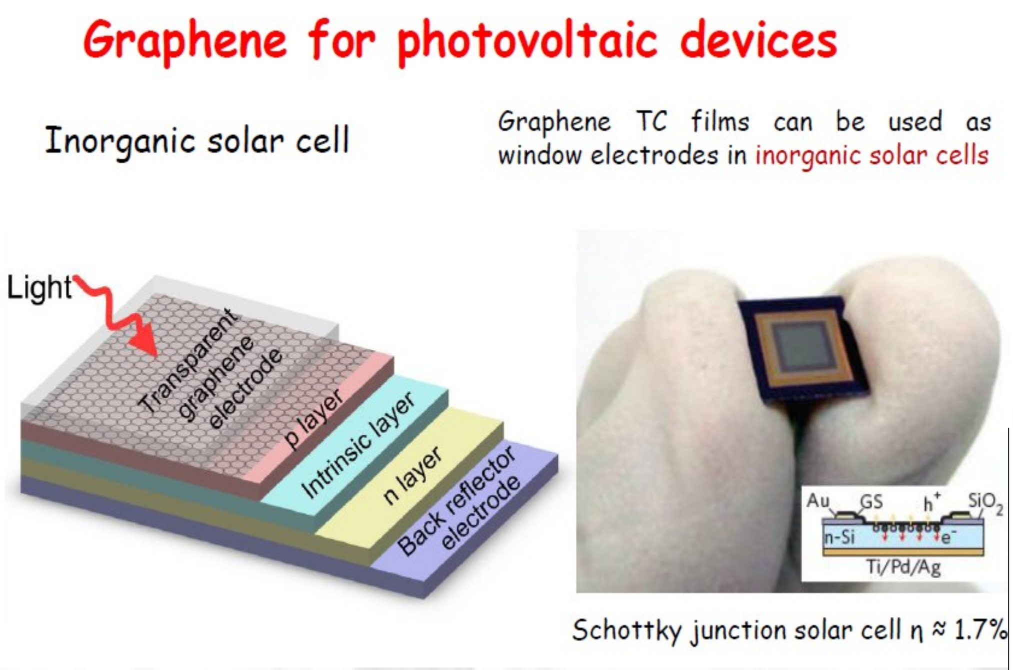


Figure 1 | A schematic representation of a hybrid battery–capacitor device, in which an intercalation material would be used as the cathode (left) and graphene as the anode material (right). Lithium ions (yellow) are inserted and de-inserted during charge and discharge cycles. Figure reproduced with permission from ref. 16, © 2011 Wiley.

Solar cell



Graphene for energy

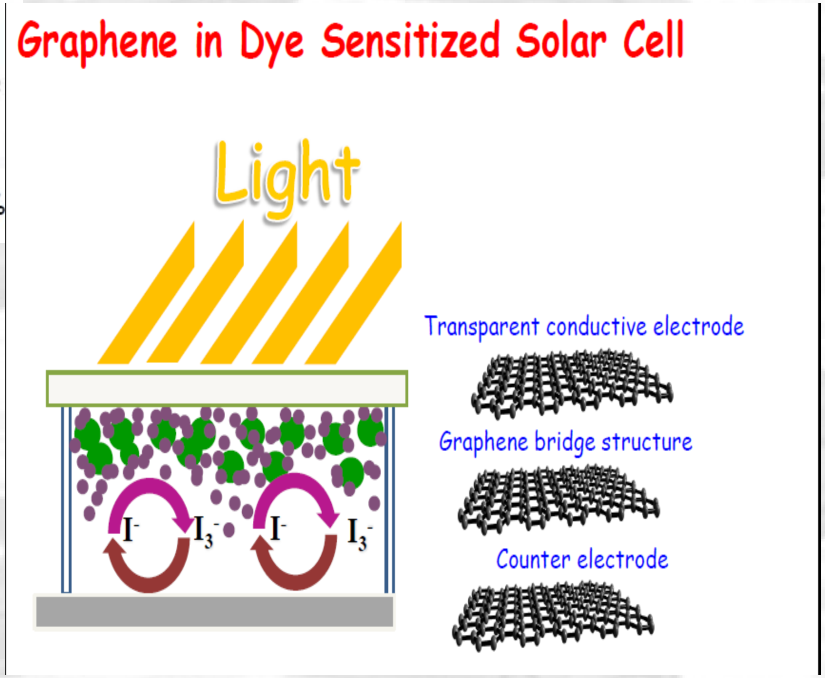


Graphene for photovoltaic devices

Inorganic solar cell

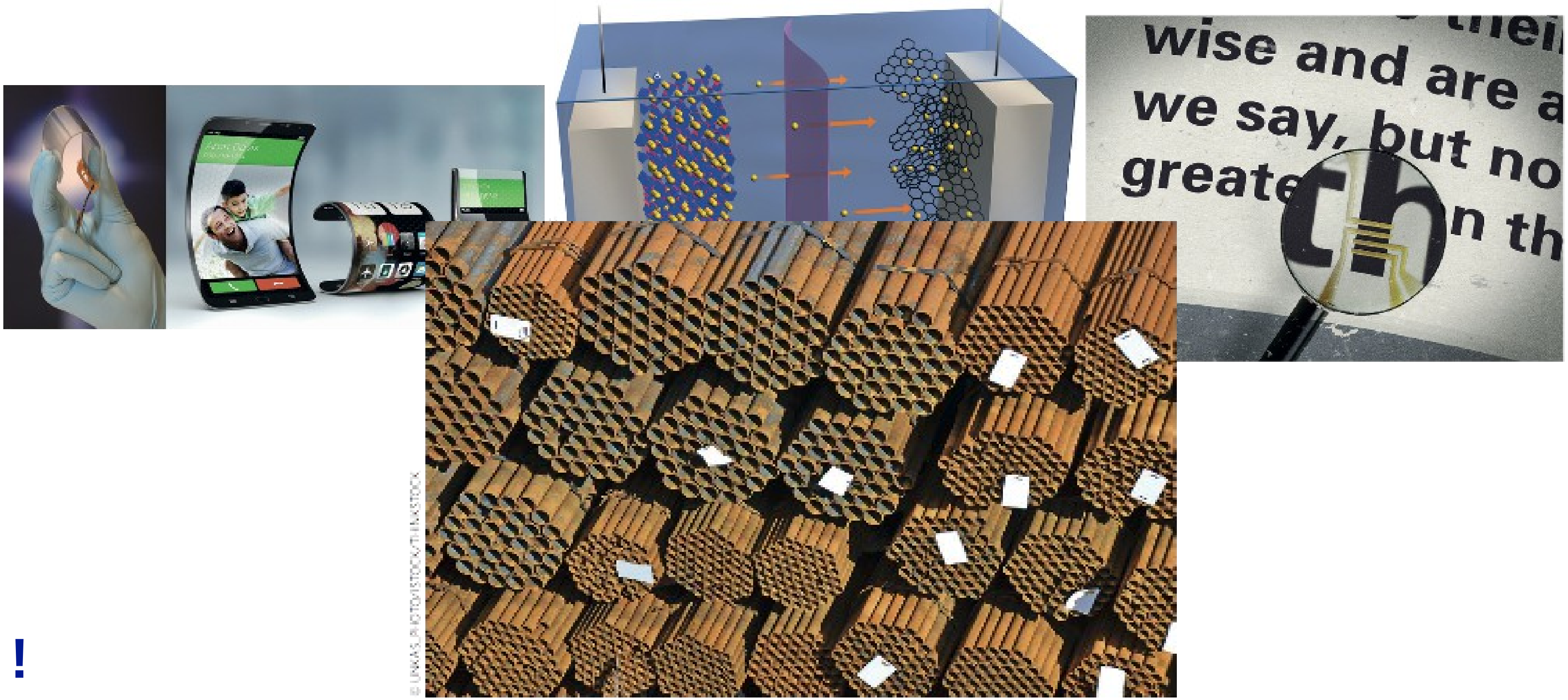
Graphene TC films can be used as window electrodes in inorganic solar cells

Schottky junction solar cell η ≈ 1.7%



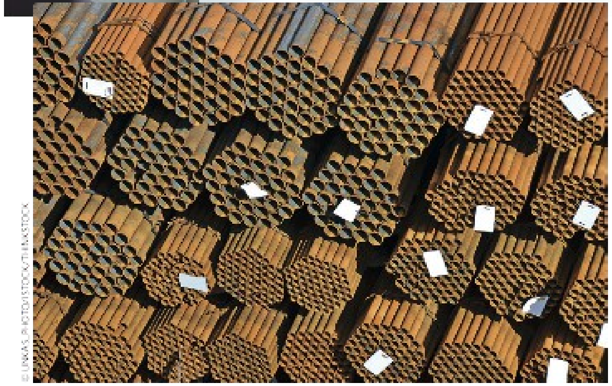
Graphene in Dye Sensitized Solar Cell

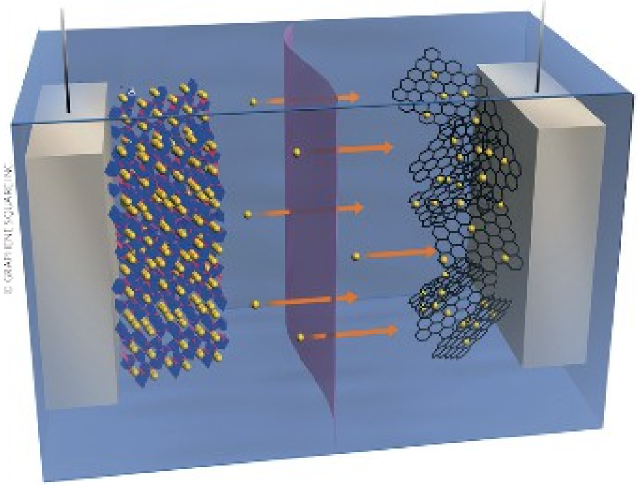
Graphene against corrosion



!

Nature Nanotechnology, 9, 737 (2014)





High electrical conductivity
High Thermal conductivity
Mechanical strength
Trasparency
Impermeability
Biological compatible

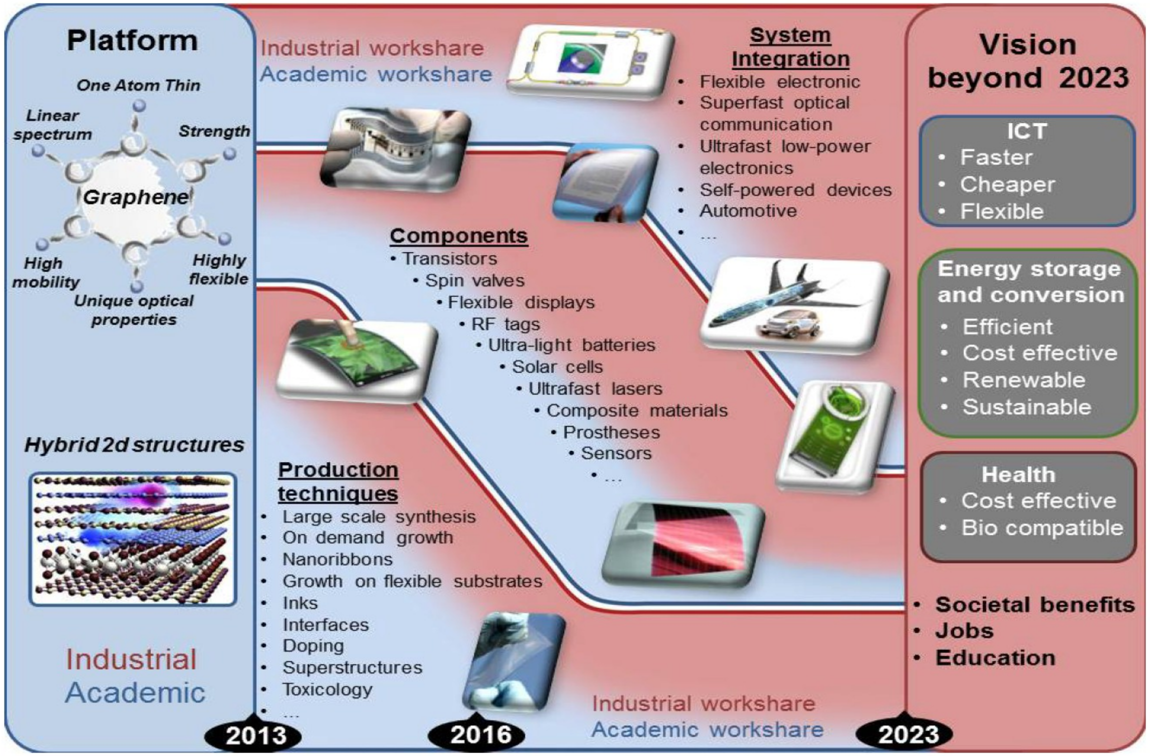
Flexible electronics
Energy devices
Sensors
Smart textile
Smart windows
……….

The roadmap of the graphene flagship?

The European Union has identified graphene as future material for translational nanotechnology and the Graphene Flagship, a 1 billion euro venture, has been launched on October 10th 2013. The mission of the Graphene Flagship is *"to take graphene and related layered materials from academic laboratories to society, revolutionize multiple industries, and create economic growth and new jobs in Europe"*.

http://graphene-flagship.eu/

http://graphene-flagship.eu/



Production techniques

- Large scale synthesis
- On demand growth
- Nanoribbons
- Growth on flexible substrates
- Inks
- Interfaces
- Doping
- Superstructures
- Toxicology
- ...

Components

- Transistors
- Spin valves
- Flexible displays
- RF tags
- Ultra-light batteries
- Solar cells
- Ultrafast lasers
- Composite materials
- Prostheses
- Sensors
- ...

System Integration

- Flexible electronic
- Superfast optical communication
- Ultrafast low-power electronics
- Self-powered devices
- Automotive
- ...

Vision beyond 2023

ICT

- Faster
- Cheaper
- Flexible

Energy storage and conversion

- Efficient
- Cost effective
- Renewable
- Sustainable

Health

- Cost effective
- Bio compatible

- **Societal benefits**
- **Jobs**
- **Education**

Figure 1-7: *European graphene roadmap for the period of 2013-2023 and beyond for exploitation of graphene for a wide range of applications in ICT, energy, materials and beyond. In a black and white printout, the darker color indicates industrial workshare and the lighter color indicates the academic workshare. As the technology matures, industrial participation will take the lead.*

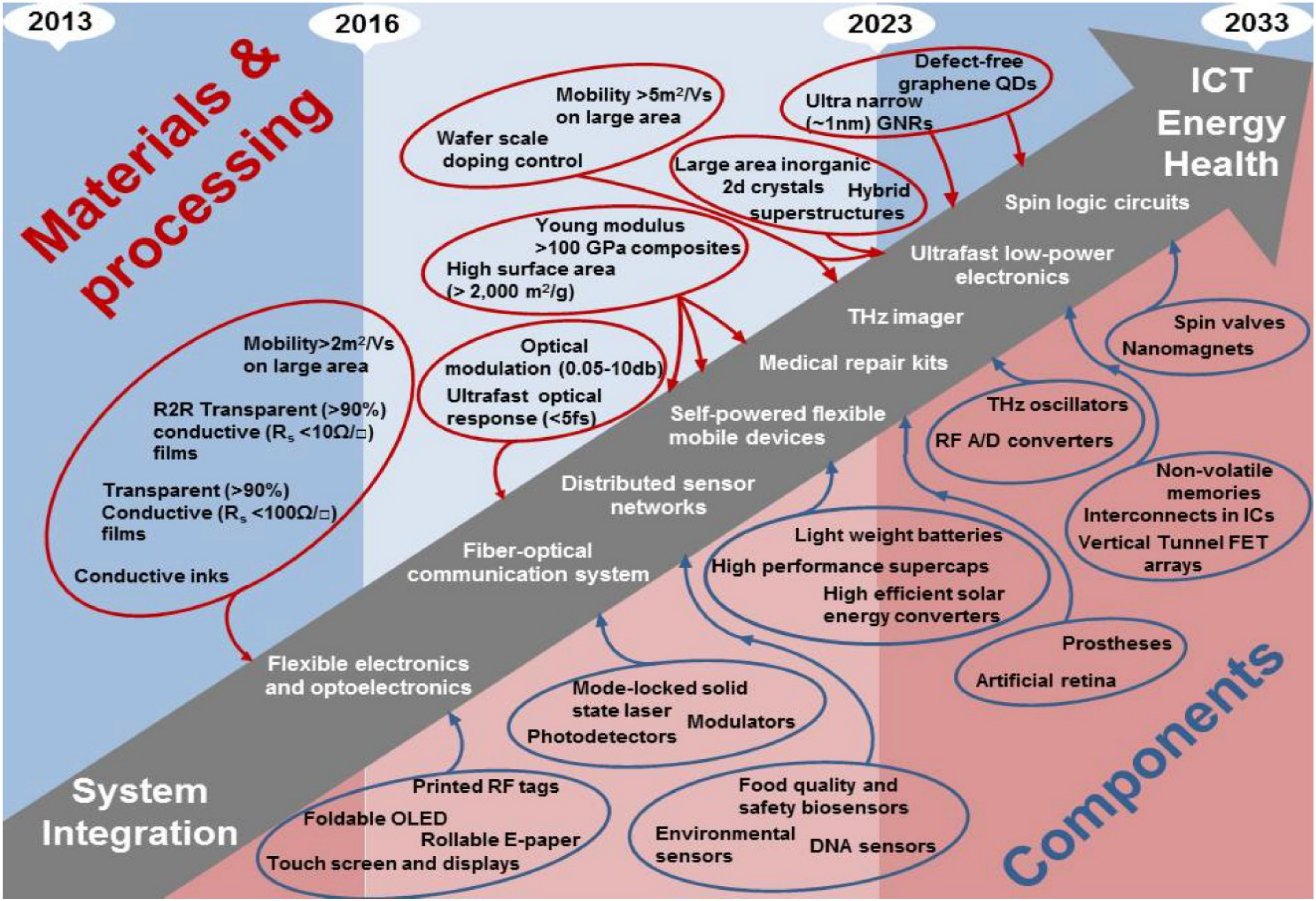
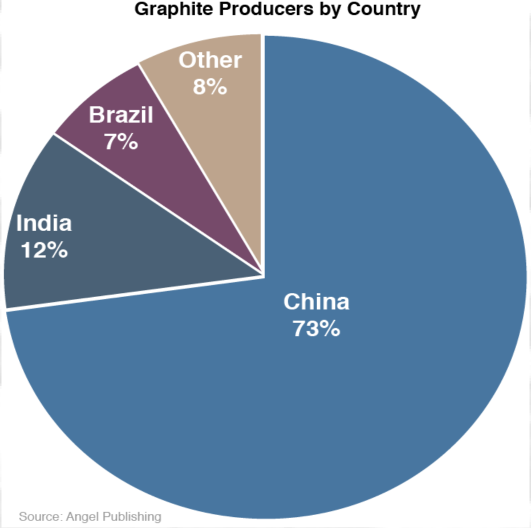


Figure 1-8: *Illustration of the detailed European graphene roadmap for the period of 2013-202 beyond for the development of materials and processes needed for a wide range of componen applications, and the vision to bring these components to market.*

The roadmap of the graphene flagship?



Research

Patent

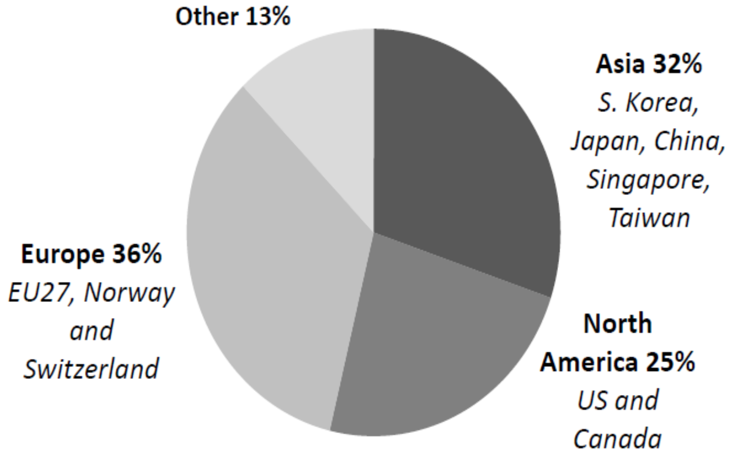


Figure 1-2 *Geographical distribution of scientific publications on graphene.*

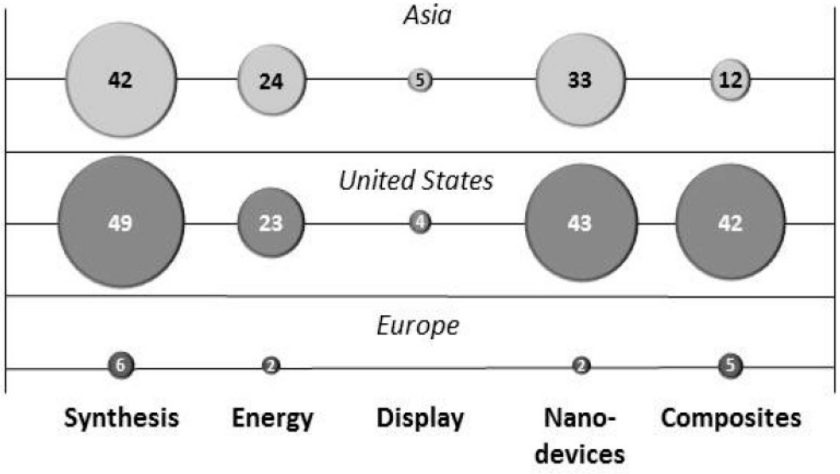


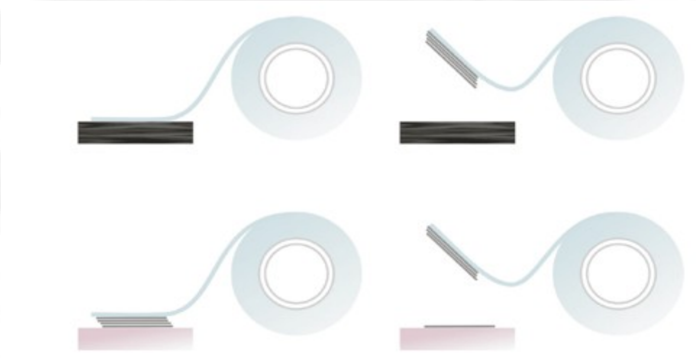
Figure 1-3 *Geographical distribution of graphene-based patent applications in specific fields.*

Is it easy to grow graphene?

Preparation methods

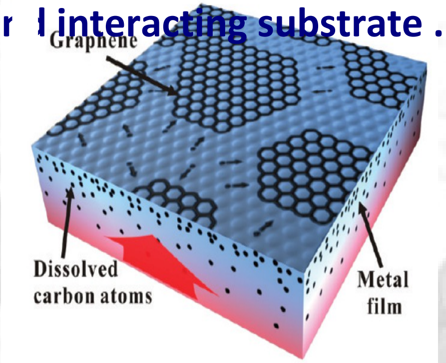
Top-down approach
(From graphite)

Bottom up approach
(from carbon precursors)



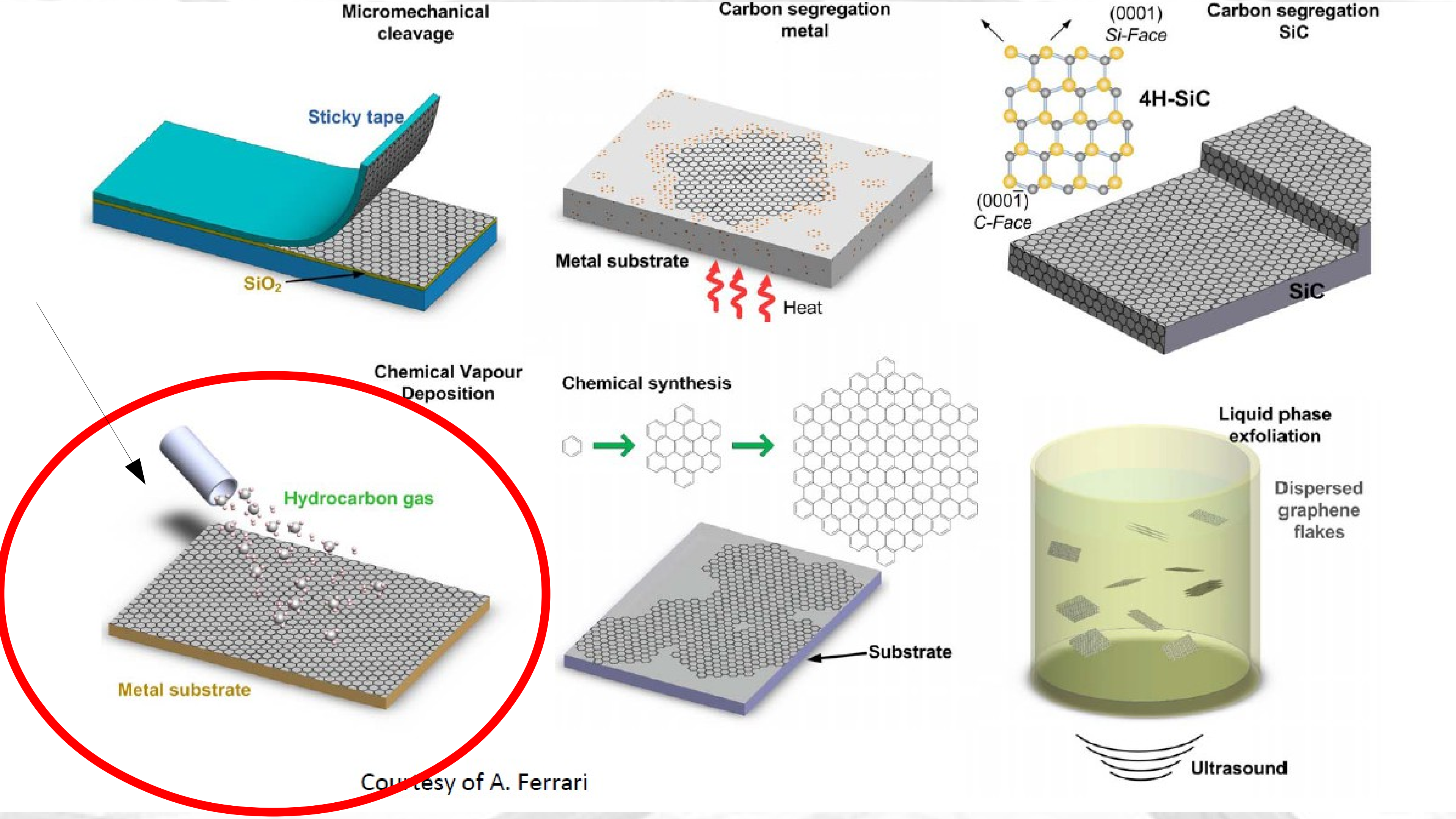
Carbon segregation from metals

Crystals of 1cm^2,imperfections and interacting substrate ...



Nan L. et al., Nano lett., **11**,297 (2011)

Is it easy to grow graphene?



Courtesy of A. Ferrari

Is it easy to grow graphene? Yes

Preparation methods

Top-down approach
(From graphite)

Flakes with limited size (5-10μ)

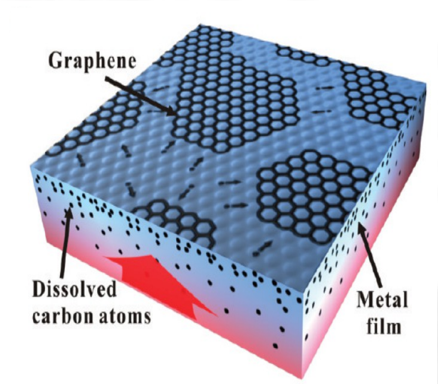
Ripples

Bottom up approach
(from carbon precursors)

Large graphene area

Regular Corrugation-
Interaction with the substrate

Carbon segregation from metals



Nan L. et al., Nano lett., **11**,297 (2011)

Graphene on metal substrates

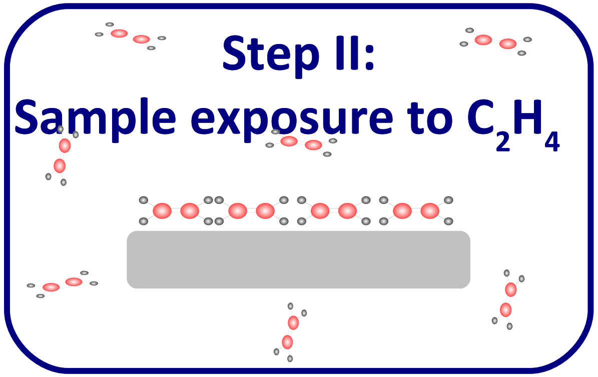
Catalytic hydrocarbon decomposition

Step I:

Sample cleaning in UHV
P=10^{-10} mbar

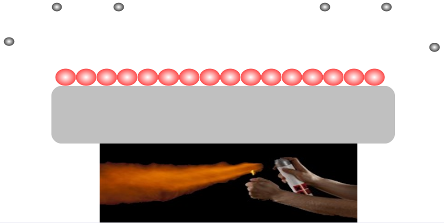
Step II:

Sample exposure to C_2H_4



Step III:

annealing at 1200K

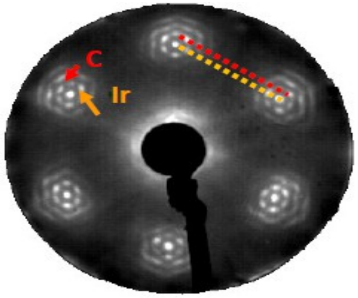


Gr/Ir(111)

Lattice constants mismatch: moiré pattern!

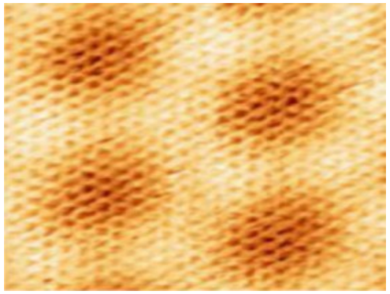
Gr 2.45
Å 2.71 Å

LEED



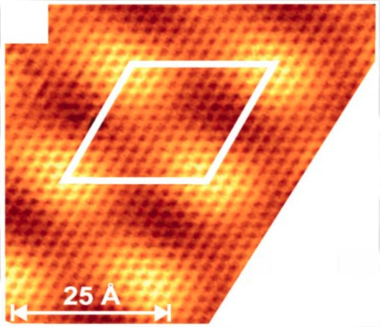
Betti et al., J. Nanopart. Res., **13**, 6013 (2011)

STM



Pletikosic et al., *Phys. Rev.* **102**, 056808 (2009)

Graphene on transition metals

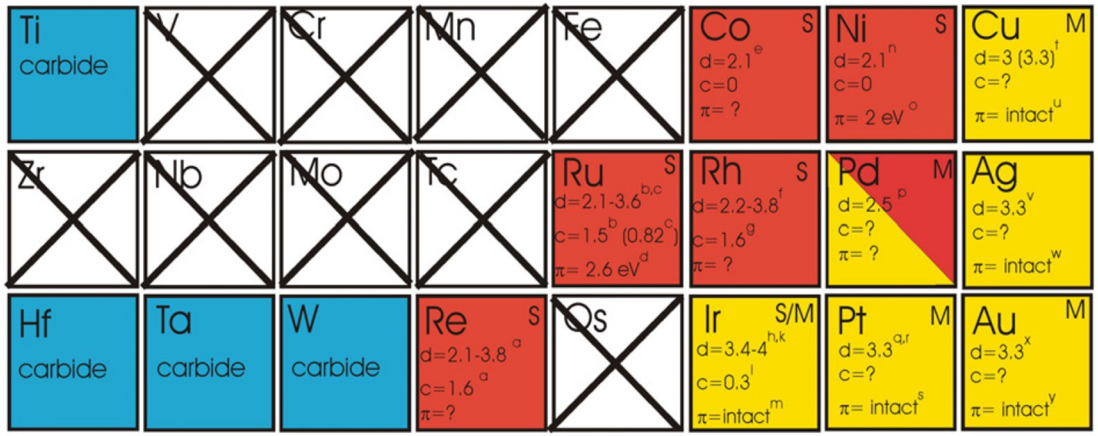


Hydrocarbons decomposition

<u>High quality monolayer graphene</u>

Alpha T. N'Diaye, et al. PRL **97,** 215501 (2006)

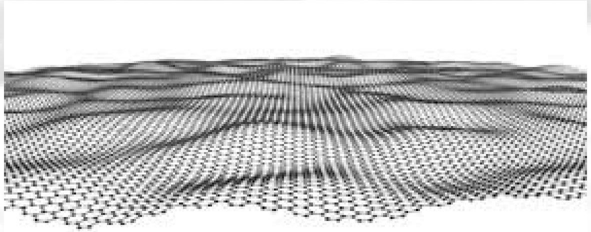
M. Batzill, Surface Science Reports **67** (2012) 83–115



Ti carbide	V	Cr	Mn	Fe	Co S d=2.1[e] c=0 π= ?	Ni S d=2.1[n] c=0 π= 2 eV[o]	Cu M d=3 (3.3)[t] c=? π= intact[u]
Zr	Nb	Mo	Tc	Ru S d=2.1-3.6[b,c] c=1.5[b] (0.82[c]) π= 2.6 eV[d]	Rh S d=2.2-3.8[f] c=1.6[g] π= ?	Pd M d=2.5[p] c=? π= ?	Ag d=3.3[v] c=? π= intact[w]
Hf carbide	Ta carbide	W carbide	Re S d=2.1-3.8[a] c=1.6[a] π=?	Os	Ir S/M d=3.4-4[h,k] c=0.3[l] π=intact[m]	Pt M d=3.3[q,r] c=? π= intact[s]	Au M d=3.3[x] c=? π= intact[y]

Increase of the interaction strenght

- less C / TM distance
- π – d hybridization



Preobrajenski et al., *Phys. Rev. B* **78**, 073401 (2008)

Transition metal surfaces:

5d - Ir(111), Pt(111)

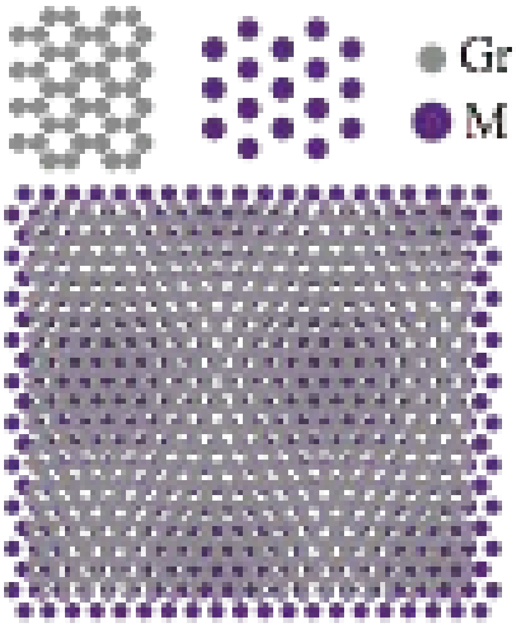
4d - Ru(0001), Rh(111)

3d - Ni(111)

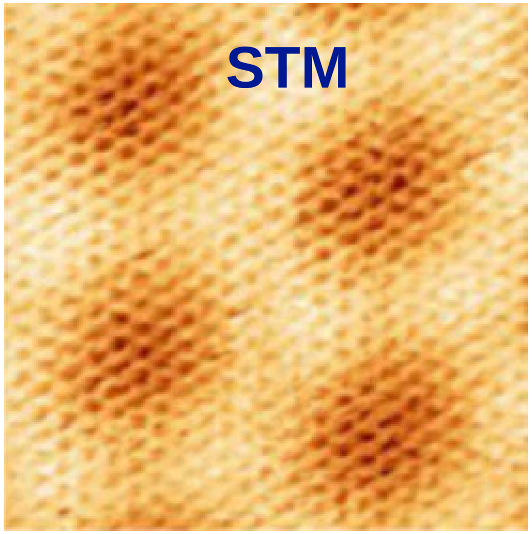
Graphene on Ir(111)

Low interaction

Slight corrugation (moiré effect)



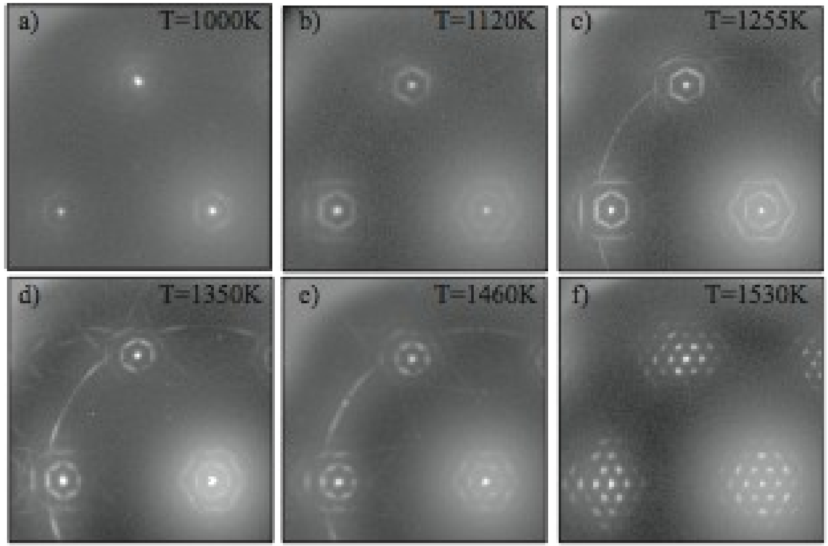
Metal	|a|
Gr	2.46Å
Co(0001)	2.51Å
Ni(111)	2.49Å
Pt(111)	2.77Å
Ir(111)	2.72Å
Ru(0001)	2.71Å
Rh(111)	2.69Å



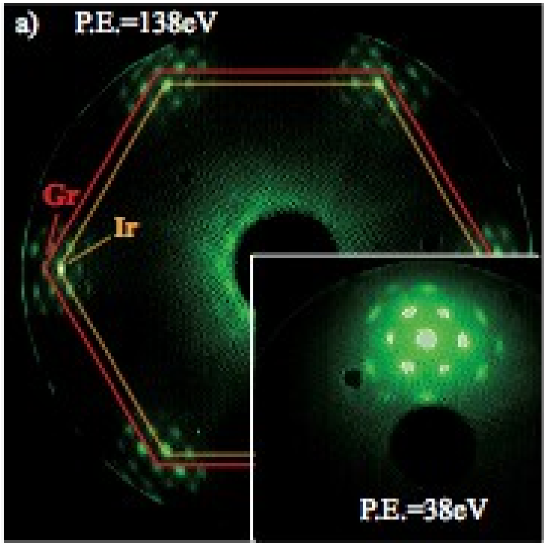
Pletikosic et al., *Phys. Rev. Lett.* **102**, 056808 (2009

Graphene on Ir(111)

High quality and long range ordered sheets



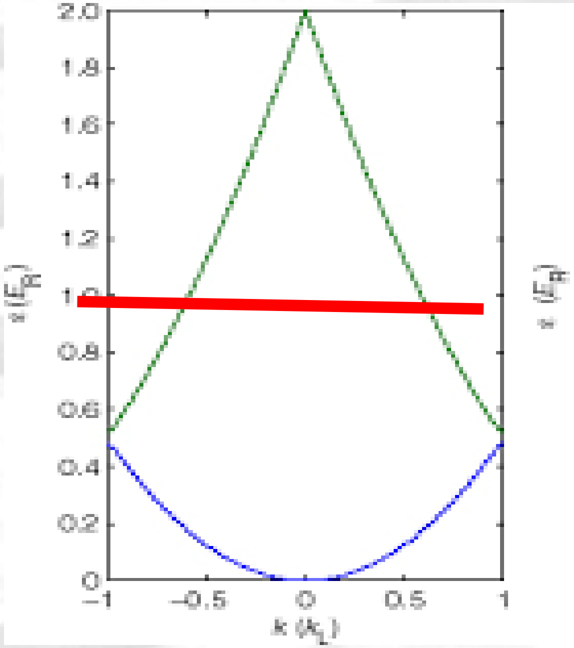
LEED diffraction pattern from Hattab, H. et al., Apple. Phys. Lett. 98 141903 (2011)



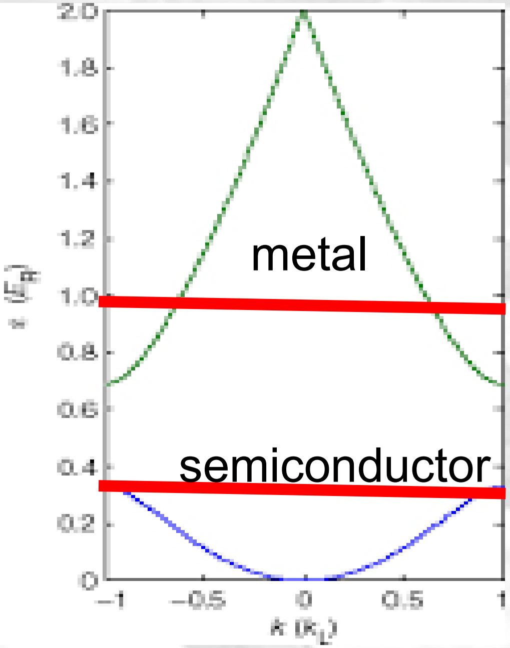
LEED diffraction pattern
In LOTUS lab

Electrons in graphene: velocity

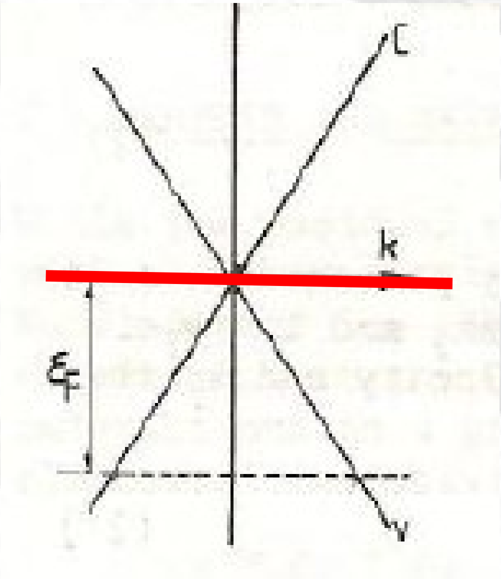
Free electron



Electrons in a periodic potential



Electrons in graphene



$E=\hbar k^2/2m$

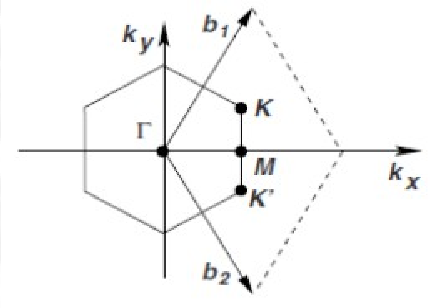
Velocity $=dE/dk$

$E=v_F k$

$v=dE/dk=\text{constant}$

Electronic properties

Tight binding solution for energy dispersion in the whole Brillouin zone



$$E(\mathbf{k}) = \sqrt{1 + 4cos\left(\sqrt{3}ak_y/2\right) cos(ak_x/2) + 4cos^2\left(ak_x/2\right)}$$

Close to the K point

$$E(\mathbf{k}) = \nu_f K$$

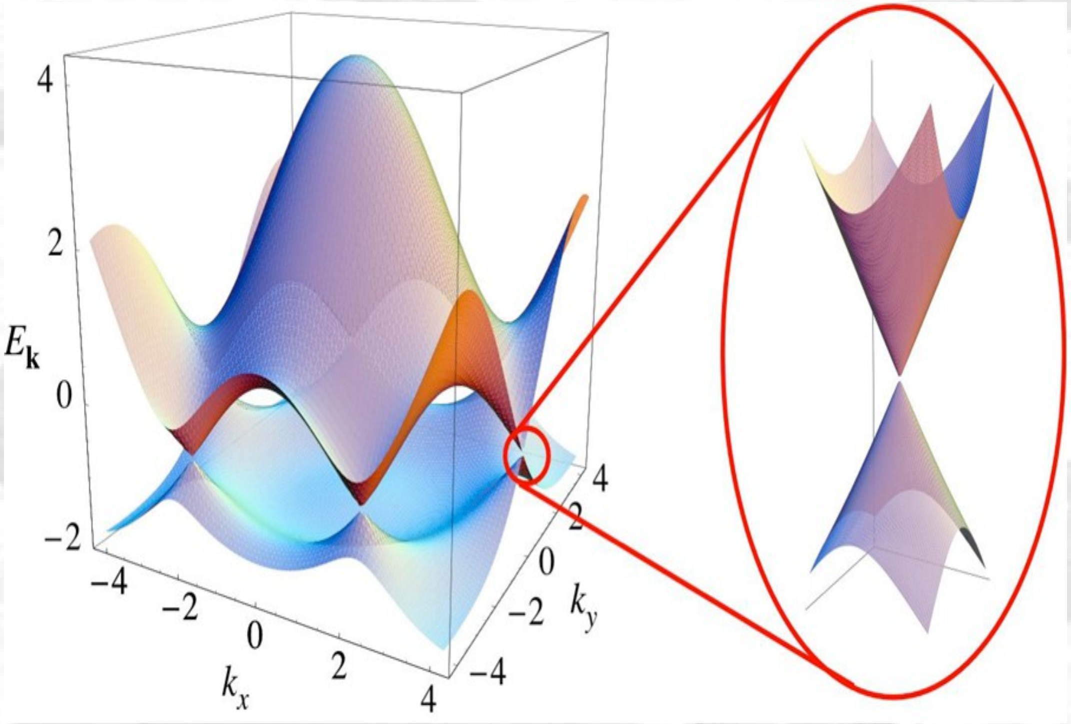
$$H = \begin{pmatrix} 0 & v(k_x - ik_y) \\ v(k_x + ik_y) & 0 \end{pmatrix}$$

$$H = v\vec{p}\vec{\sigma}$$

↓

2D massless Dirac particles

Hamiltonia with ν ~ 10^6 m/s

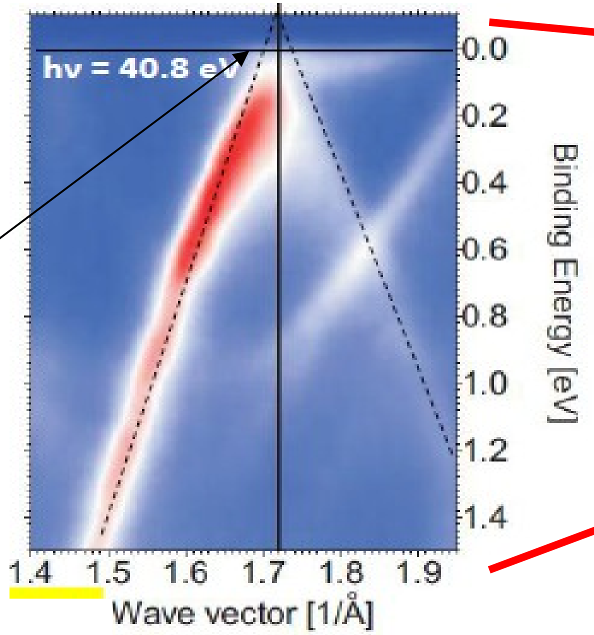


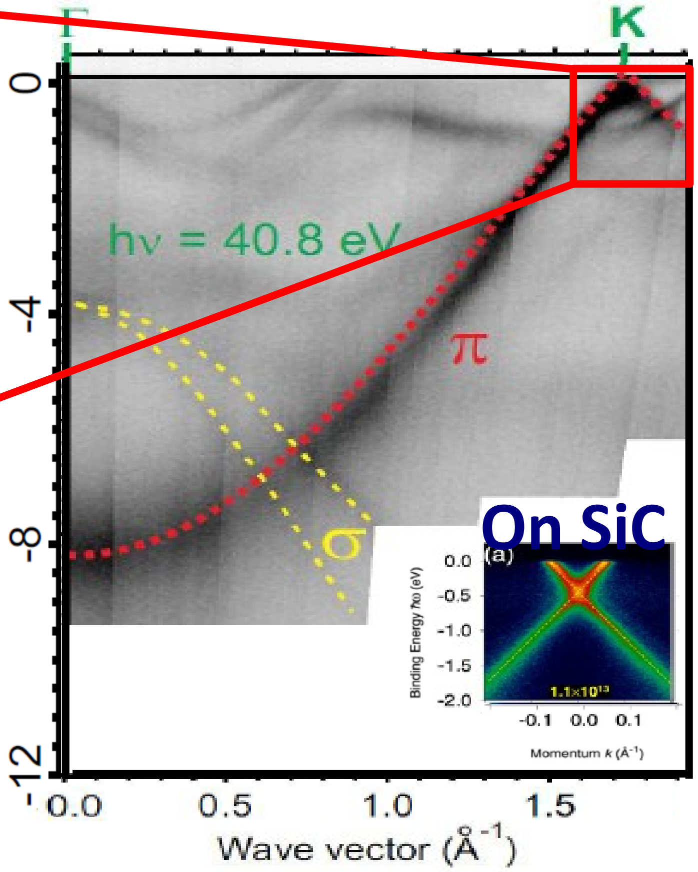
High quality graphene with low interaction with the substrate

Fermi velocity measurements!!!!!

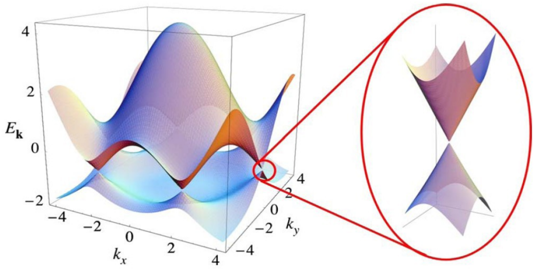
$V_{\Gamma K} = (11.6 \pm 0.5) \cdot 10^5$ m/s

Slight p doping

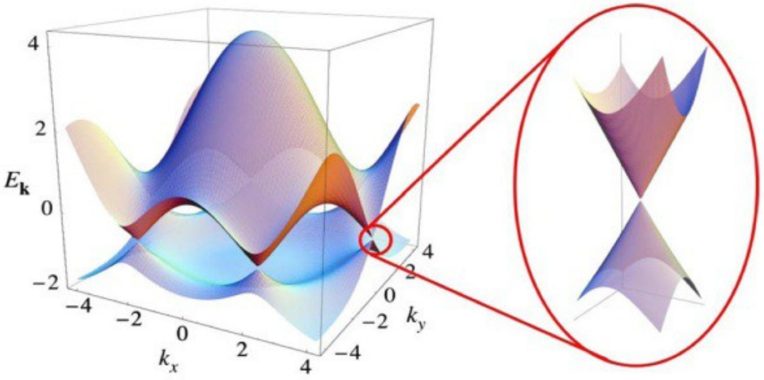


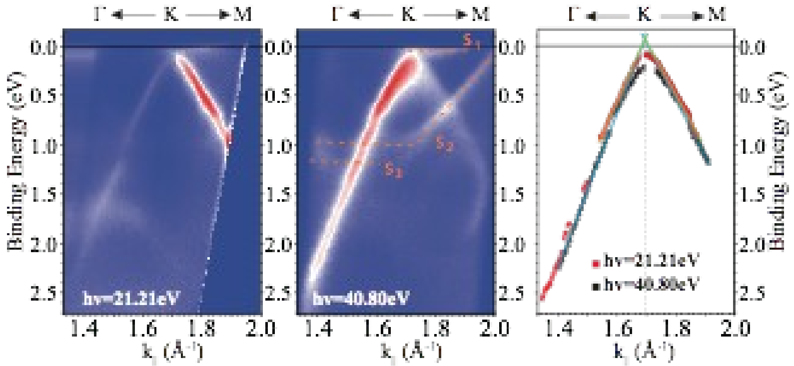


$$E(\mathbf{k})_{\pm} \approx \pm \hbar v_F |\mathbf{k}|$$

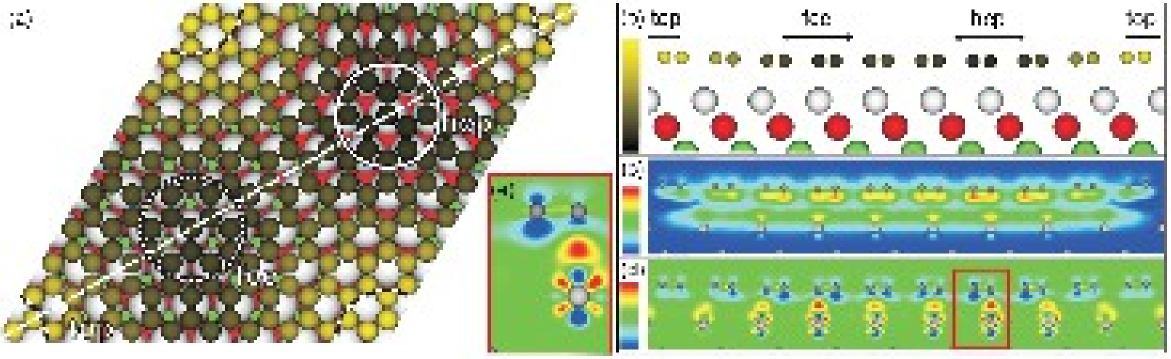


High quality graphene with low interaction with the substrate





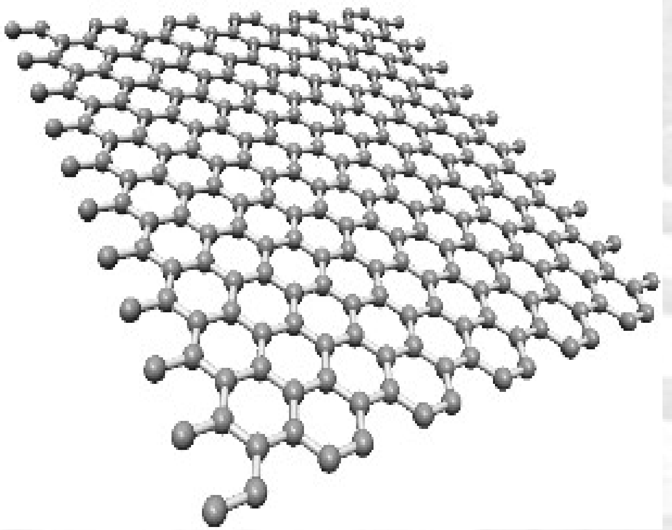
Ideal electronic properties



Almost flat in spite of the moiré supercell

High quality graphene with low corrugation

Outline



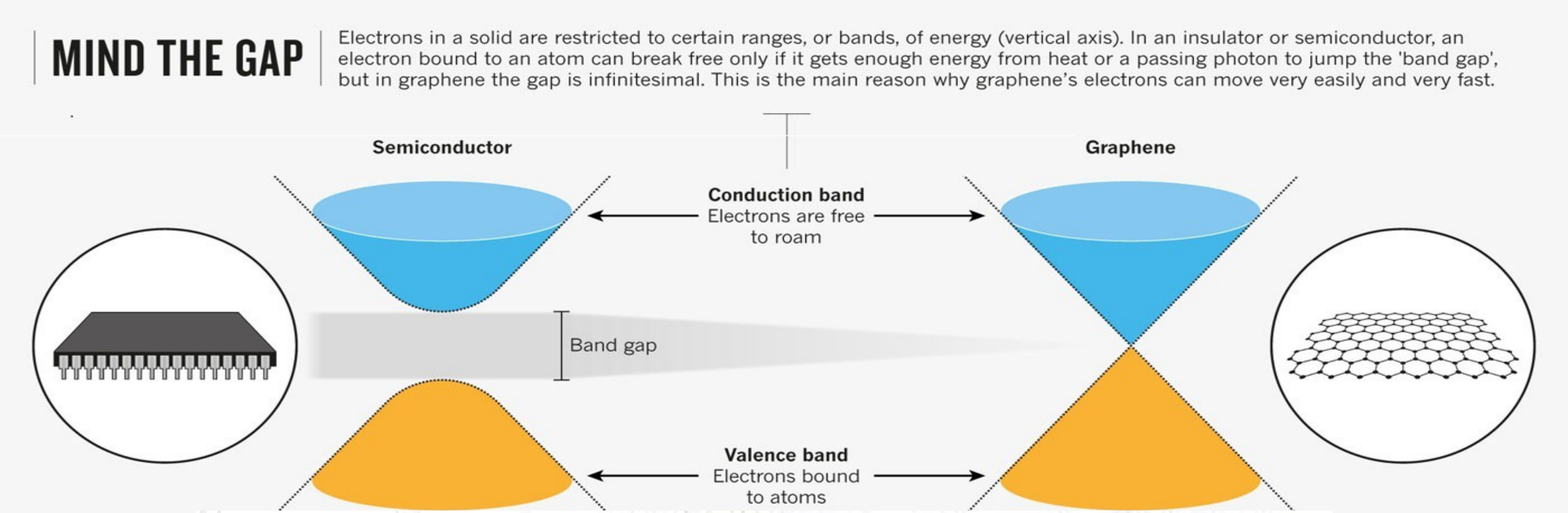
5-Is it easy to grow graphene? YES, we can

6-How to control and design the graphene properties?

7-Three examples:

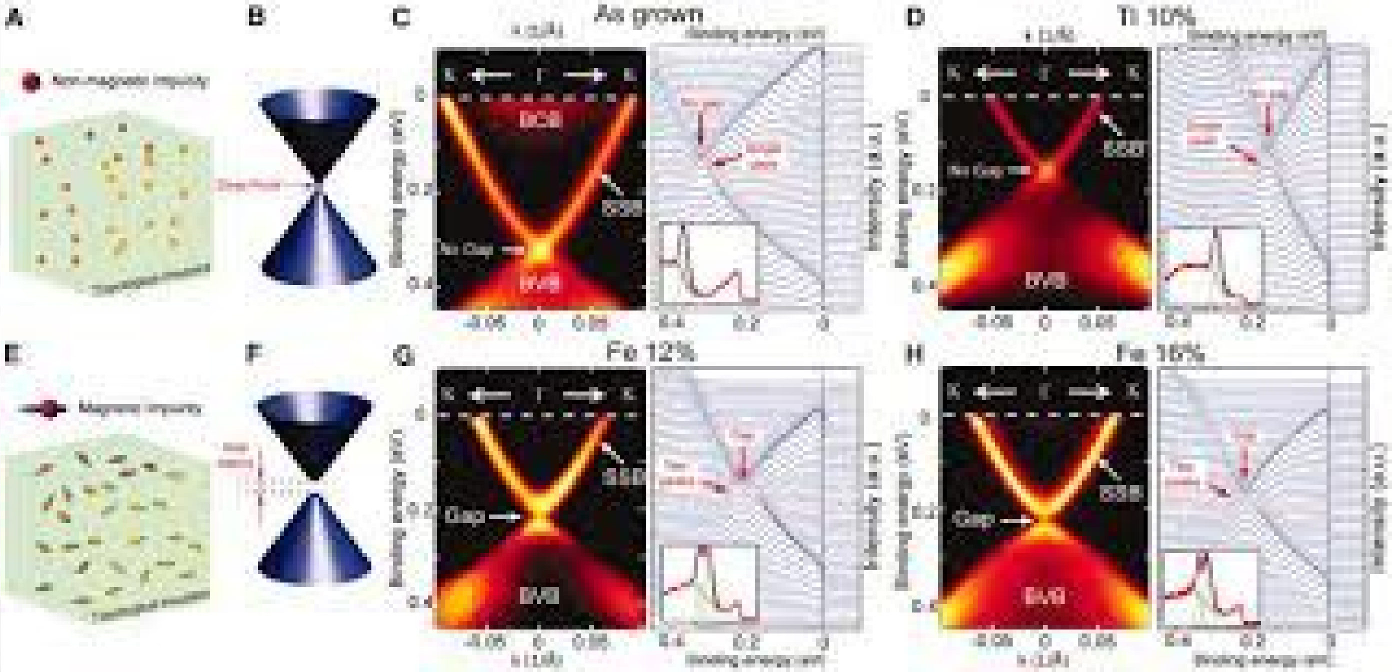
- **i) graphene: metal or semiconductor?**
- **ii) graphene a buffer layer for spintronics**
- **iii) graphene for energy storage and Li batteries**

Mind the gap

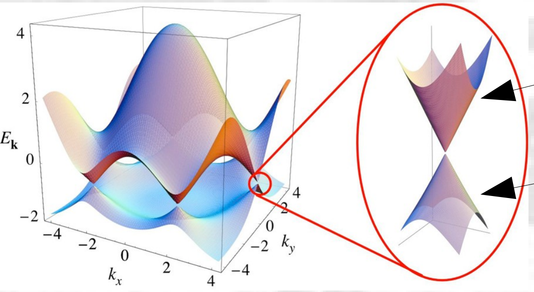


MIND THE GAP

Electrons in a solid are restricted to certain ranges, or bands, of energy (vertical axis). In an insulator or semiconductor, an electron bound to an atom can break free only if it gets enough energy from heat or a passing photon to jump the 'band gap', but in graphene the gap is infinitesimal. This is the main reason why graphene's electrons can move very easily and very fast.

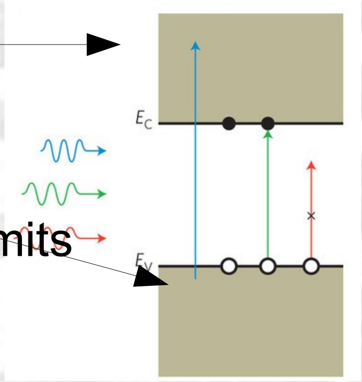


Why open a gap?



Conduction band

Valence band

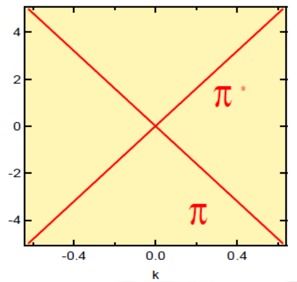


Absence of a band gap in graphene limits seriously any electronic application

Tuning the energy gap is fundamental to control the optical response and electronic and optoelectronic devices

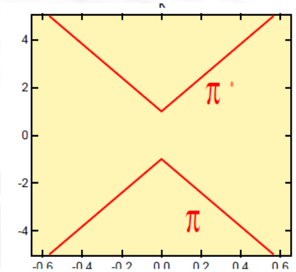
2x2 Tight Binding Hamiltonian in K point

$$H = \begin{pmatrix} 0 & \nu(k_x - ik_y) \\ \nu(k_x + ik_y) & 0 \end{pmatrix} \longrightarrow \mathrm{E}(\mathbf{k}) = \pm \nu k$$



Introducing asymmetry in electric potential

$$H = \begin{pmatrix} \frac{\Delta}{2} & \nu(k_x - ik_y) \\ \nu(k_x + ik_y) & -\frac{\Delta}{2} \end{pmatrix} \longrightarrow \mathrm{E}(\mathbf{k}) = \pm\sqrt{\nu^2 k^2 + \frac{\Delta}{4}}$$

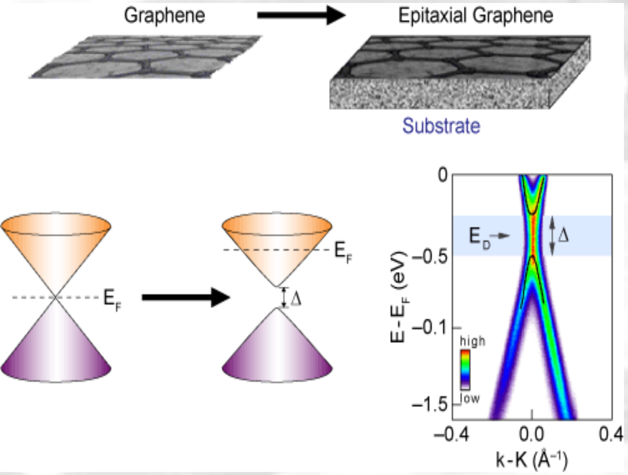


E.McCann, arXiv:1205.6953v1

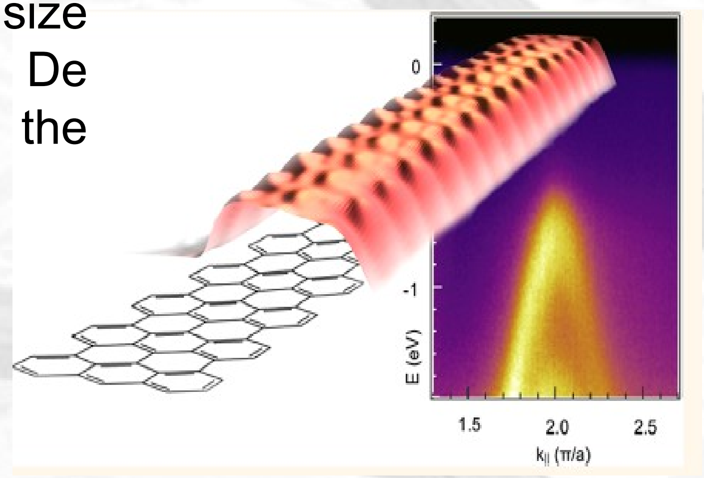
How to open a gap?

Two strategies to open a gap in a graphene sheet

1- Move from sp^2 to sp^3 hybridization induced by the substrate

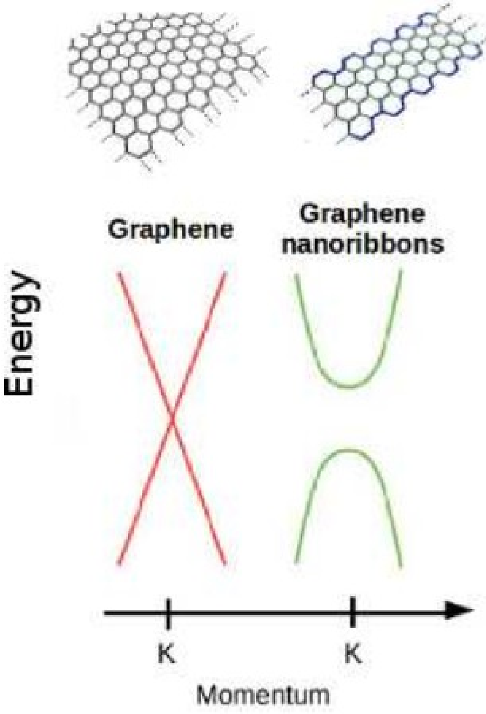


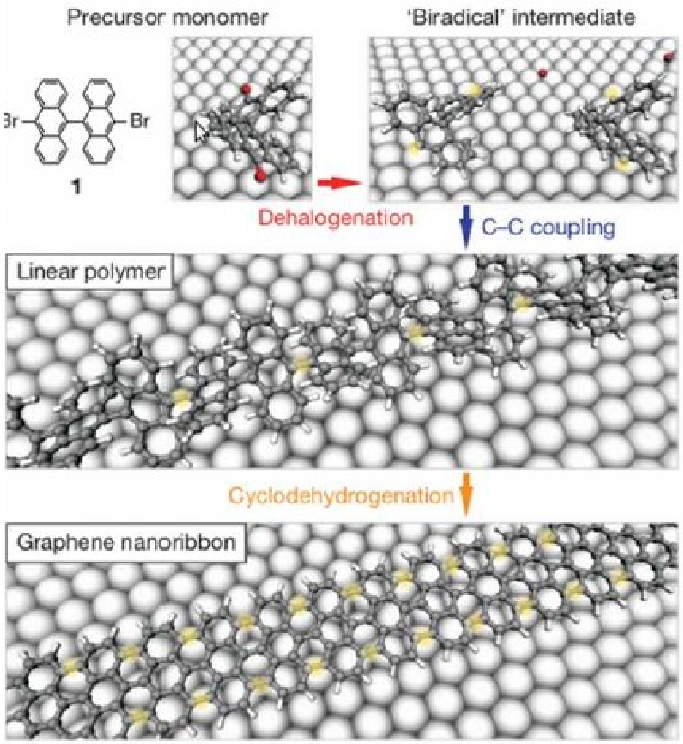
2- Confine the electrons in a nanoribbon with a lateral size comparable with the De Broglie wavelength of the electrons

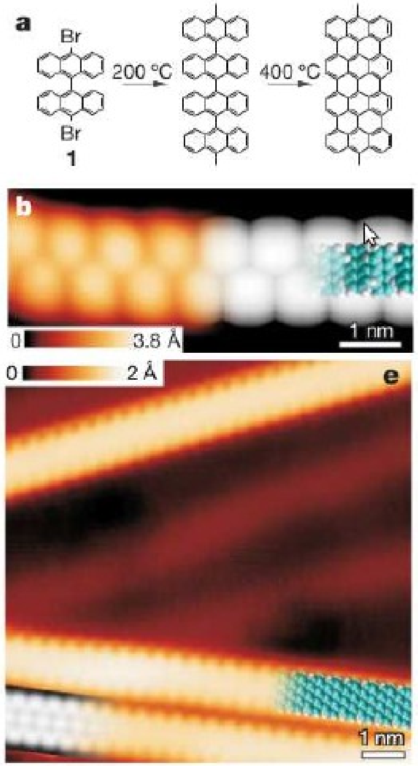


Graphene nanoribbons (GNRs)

The covalent self-assembly of 10,10-dibromo-9,9-bianthryl (DBBA) monomer precursor into 7-AGNR on the Au(111) surface

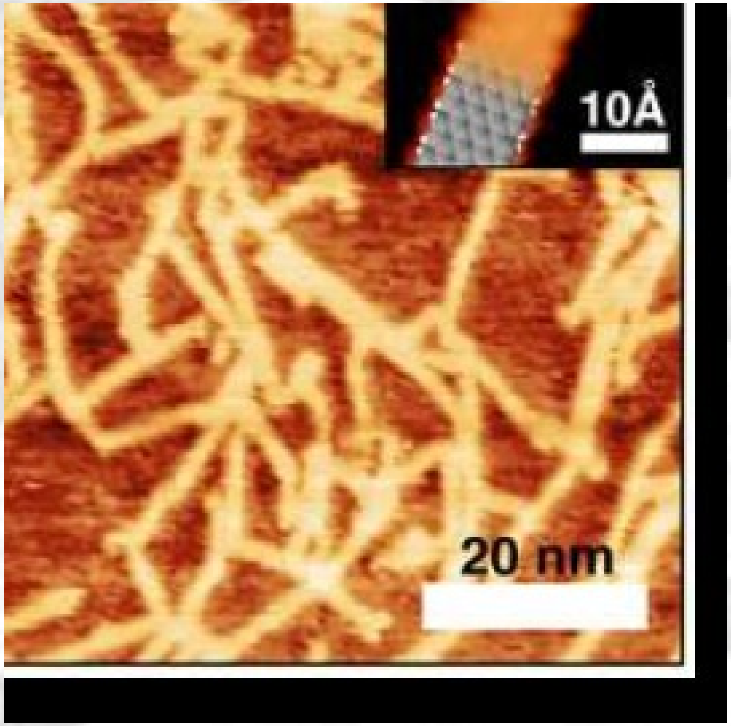




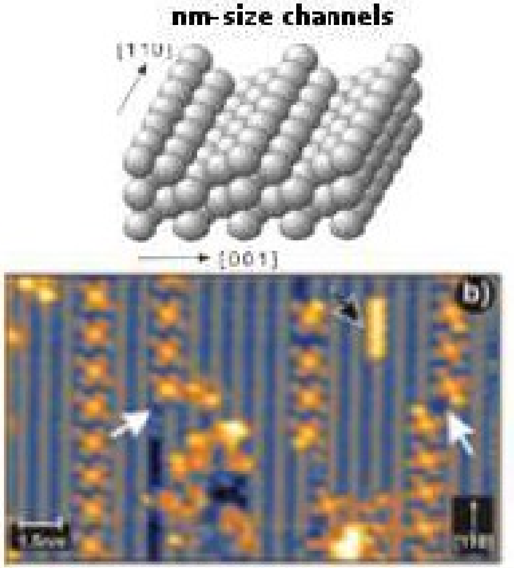


J. Cai et al., Nature, 466, 2010

Graphene nanoribbons



Graphene nanoribbons are disordered on the Au(111) surface!



S. Fortuna et al., J. Phys. Chem. C, 116, 6251, 2012

The 1x2-Au(110) surface can potentially serves as 1D template for the GNRs synthesis

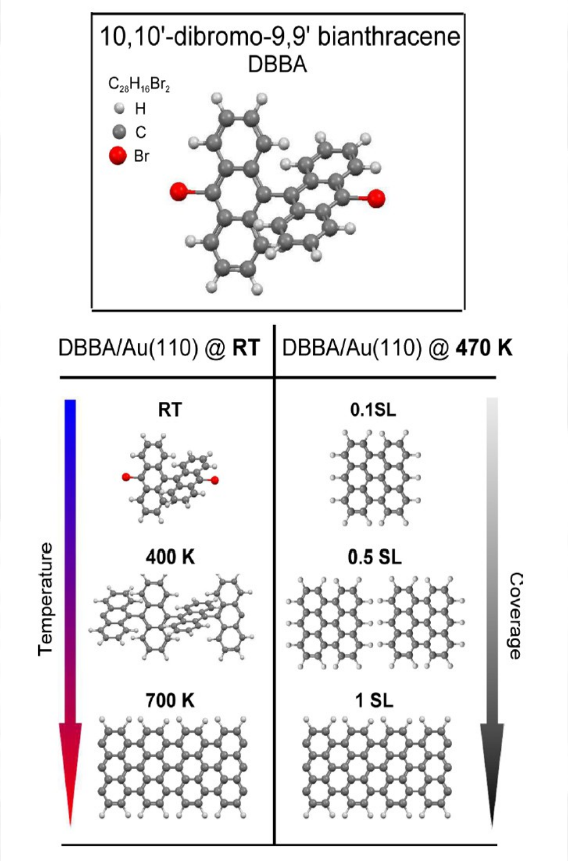
THE JOURNAL OF
PHYSICAL CHEMISTRY C

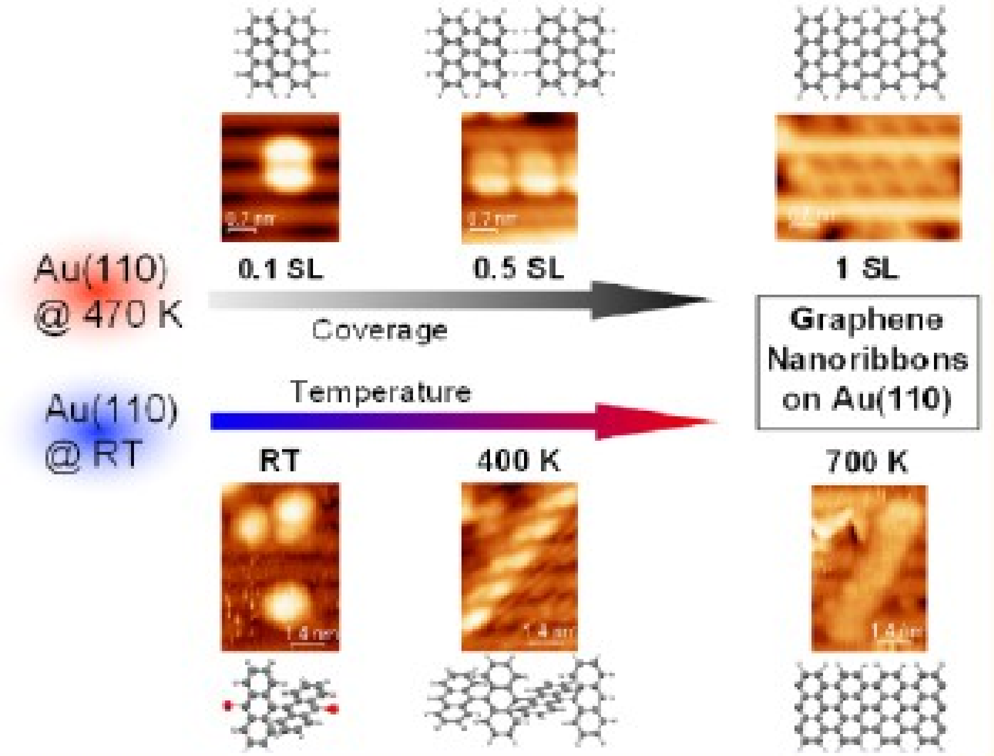
Article

pubs.acs.org/JPCC

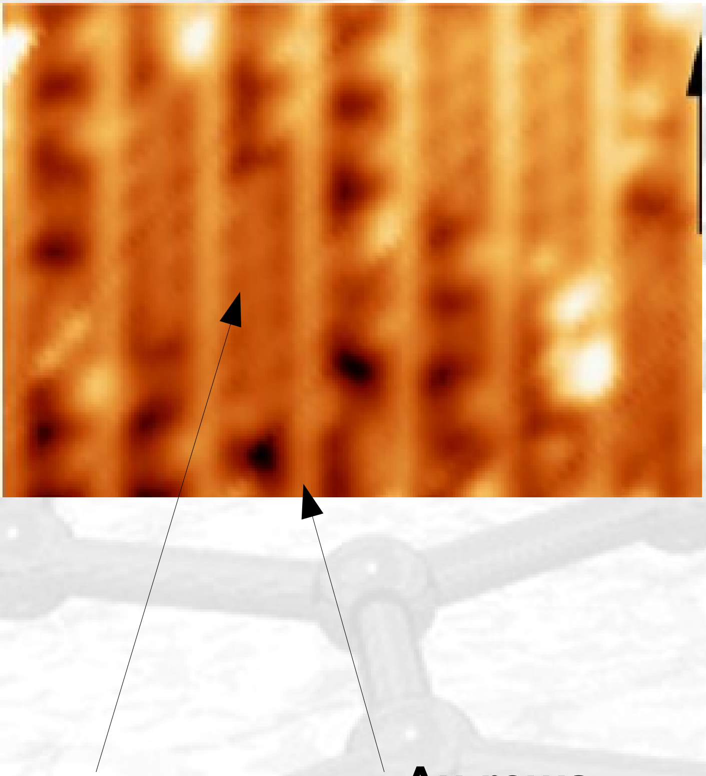
Surface-Assisted Reactions toward Formation of Graphene Nanoribbons on Au(110) Surface

Lorenzo Massimi,*,† Oualid Ourdjini,† Leif Lafferentz,‡ Matthias Koch,‡ Leonhard Grill,§,‡ Emanuele Cavaliere,∥ Luca Gavioli,∥ Claudia Cardoso,⊥ Deborah Prezzi,⊥ Elisa Molinari,⊥,# Andrea Ferretti,*,⊥ Carlo Mariani,† and Maria Grazia Betti†



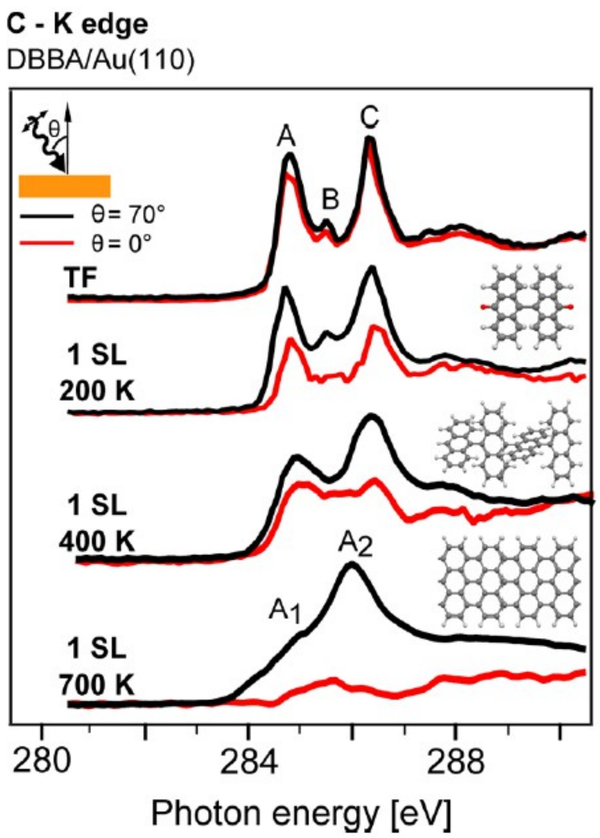


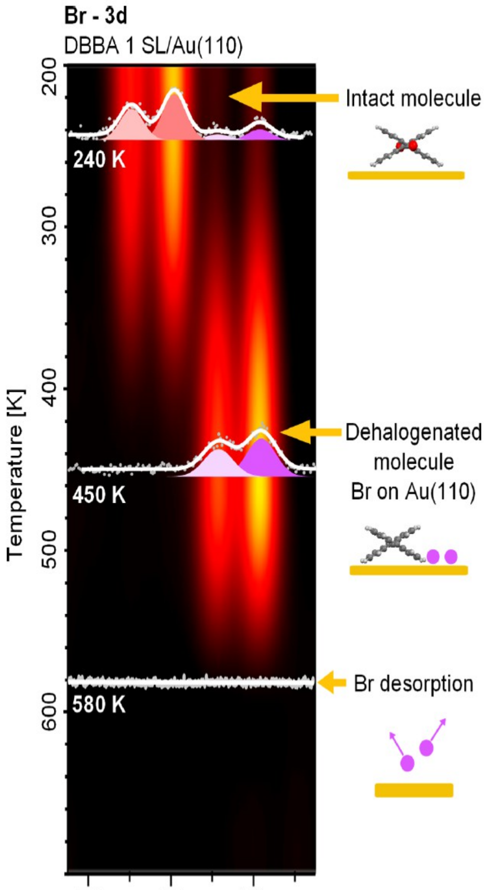
Ordered nanoribbons on Au(110) surface



Au rows

Graphene nanoribbons





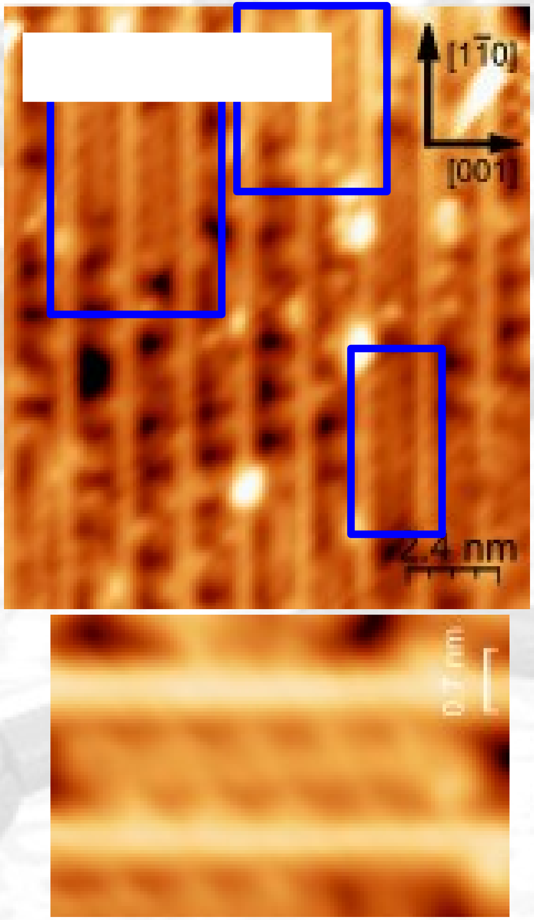
① The reconstructed 1x2-Au(110) catalyzes the chemical reactions

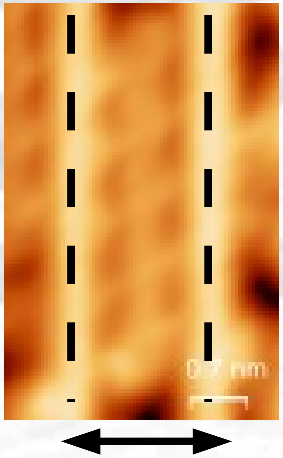
② The surface corrugation prevents the molecular diffusion

Graphene **nanoribbons**

Nanoribbon on Au(111) vs Nanoribbon on Au(110)

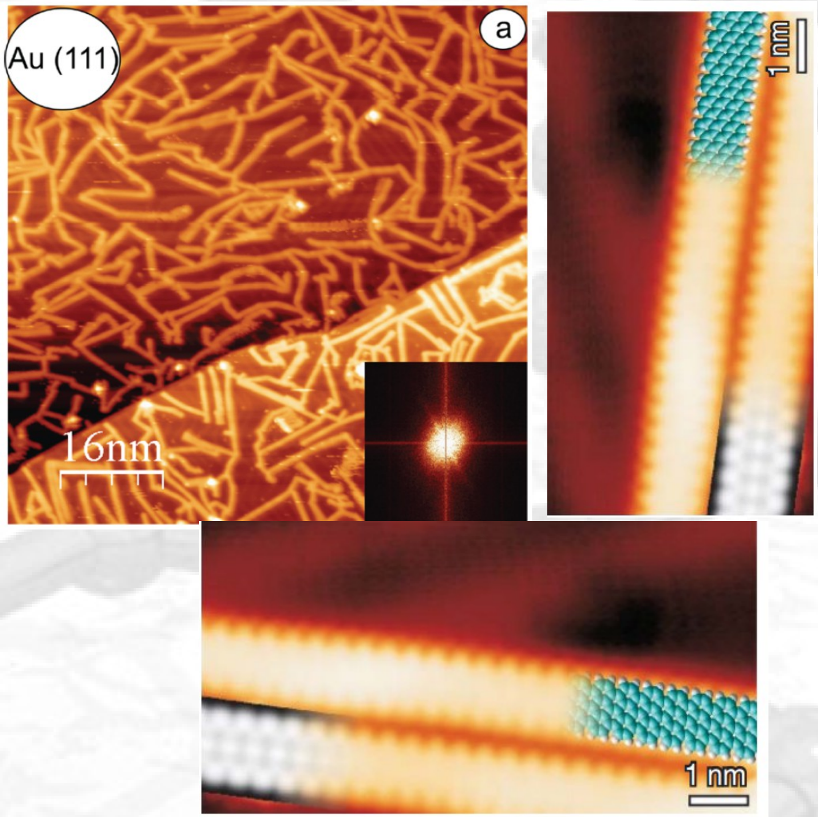
1 SL coverage





1 x 4 reconstruction

Length 5 nm



Length 20 nm

Nanoribbons on Au(110) are smaller (5 nm) than on Au(111) (>20 nm)

Lower molecular mobility due to surface roughness hinders formation of GNRs

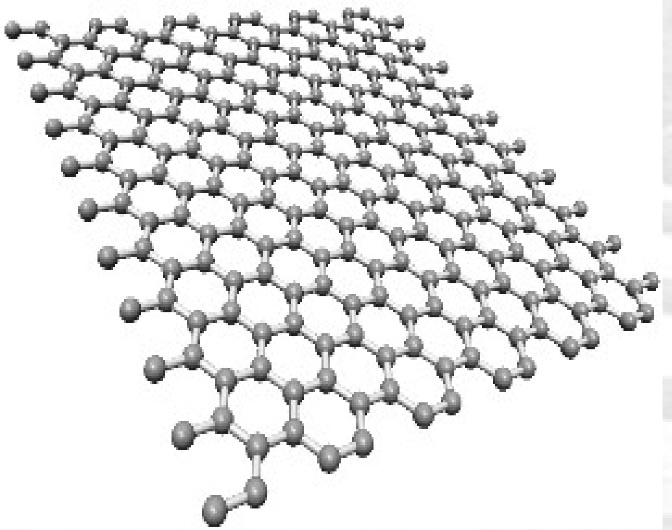
Graphene **synthesis**

1- we can grow, not only highly ordered graphene sheets, but also ordered graphene nanoribbons!

2- work in progress on the electronic structure....

3- preliminary result: gap opening at 0.7eV

Outline



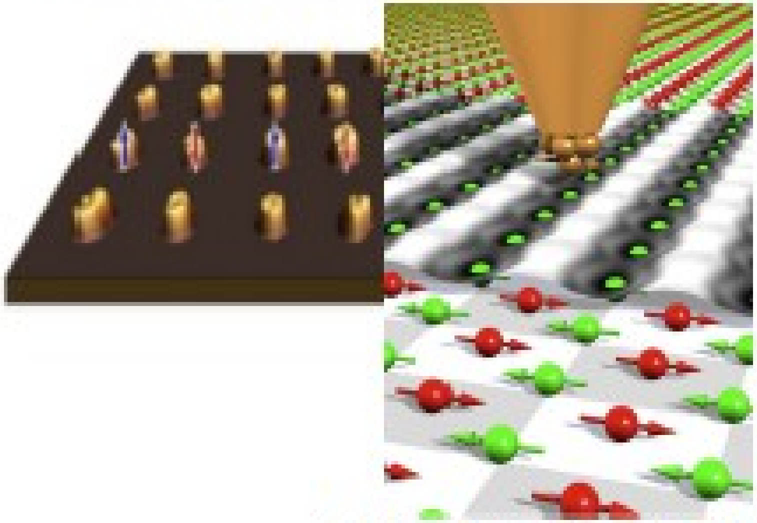
5-Is it easy to grow graphene?   YES, we can

6-How to control and design the graphene properties?

7-Three examples:

- i) graphene: metal or semiconductor?
- ii) graphene a buffer layer for spintronics
- iii) graphene for energy storage and Li batteries

Surface-supported magnetic nanostructures



S. Heinze, Science 288, 1805-1806 (2000).

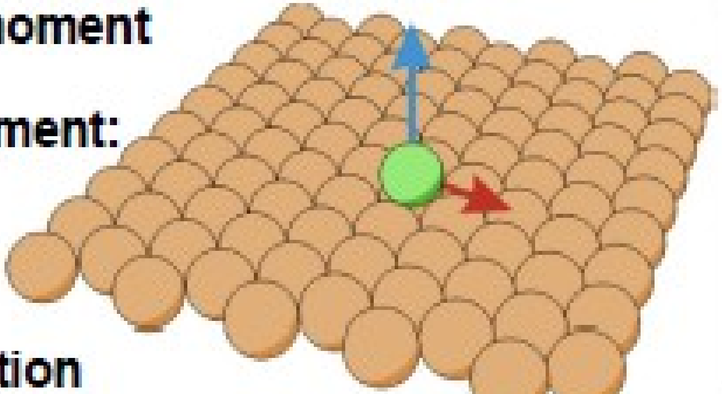
Manipulating single spins: spintronics, nanosized memory, quantum state storage...

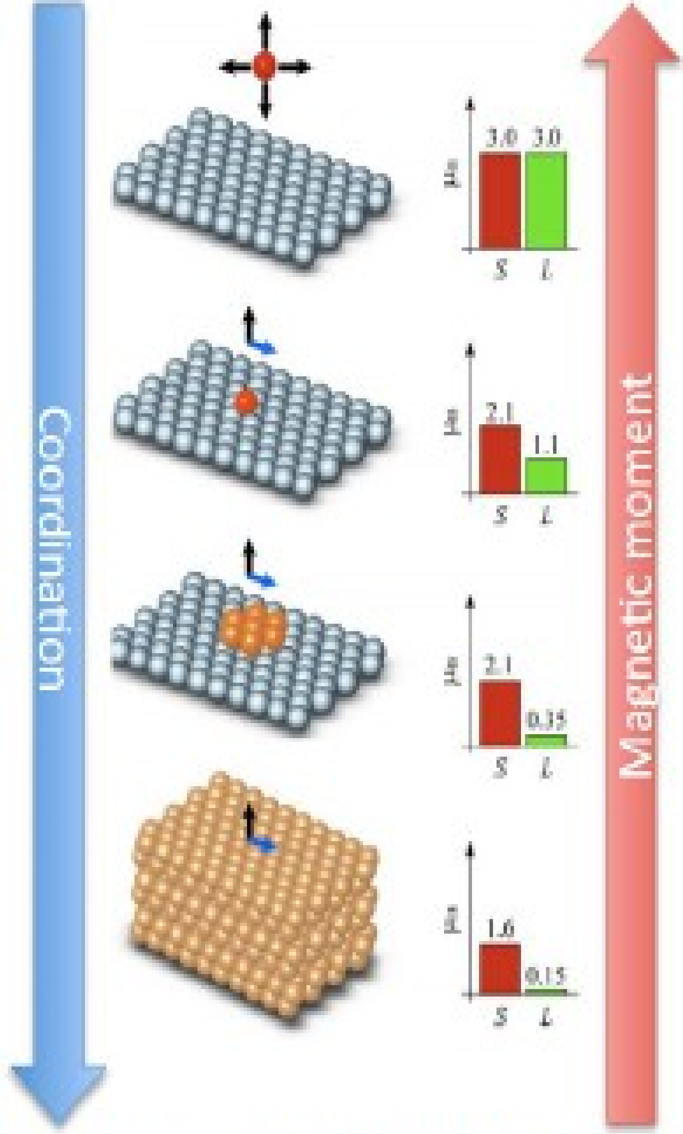
Control the magnetic properties at interfaces:

Spin and orbital moment

Chemical environment: crystal field, coordination

Interfacial interaction

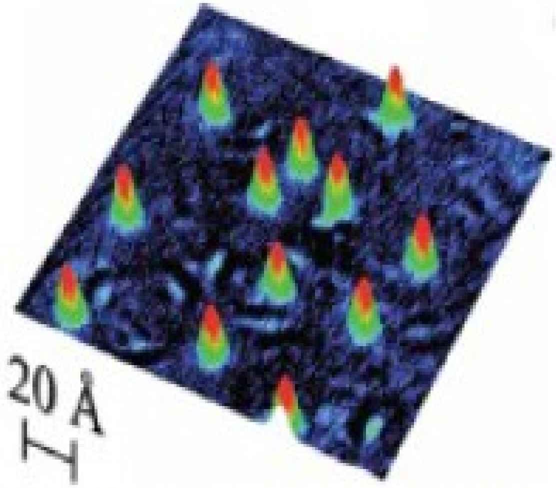




Brune, H., and Gambardella.P. Surface Science 603:1812 (2009

Ordered array of magnetically anisotropic sites

However...



Meier F. et al, Science, **320**, 82 (2008)

Lack of thermal stability

↓

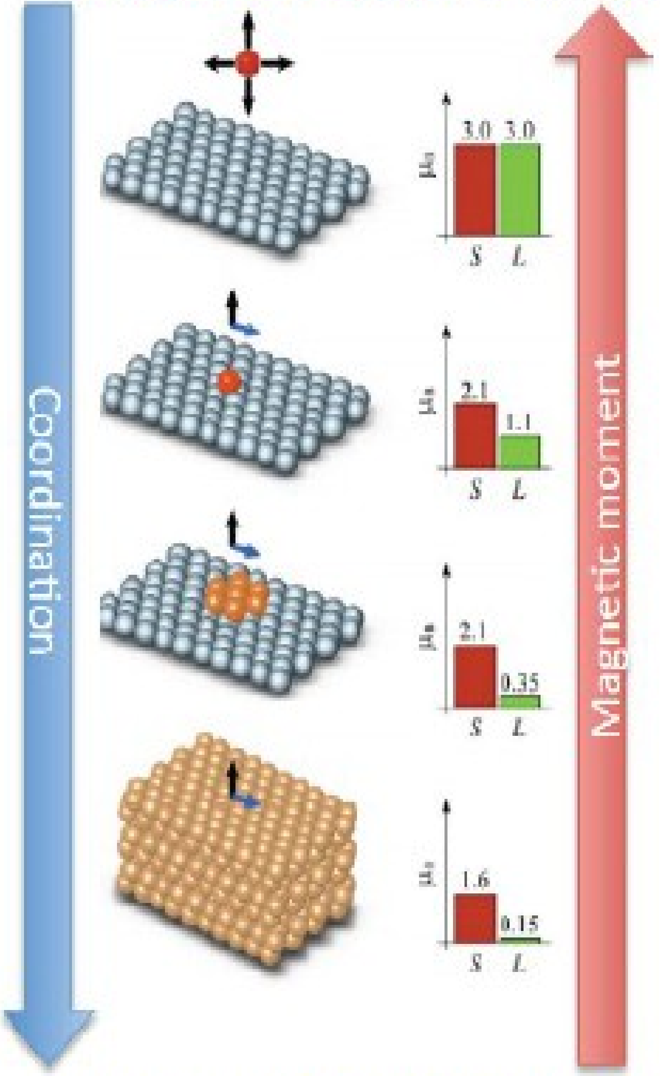
Undesired clustering

↙ ↘

No long range order

Magnetic quenching

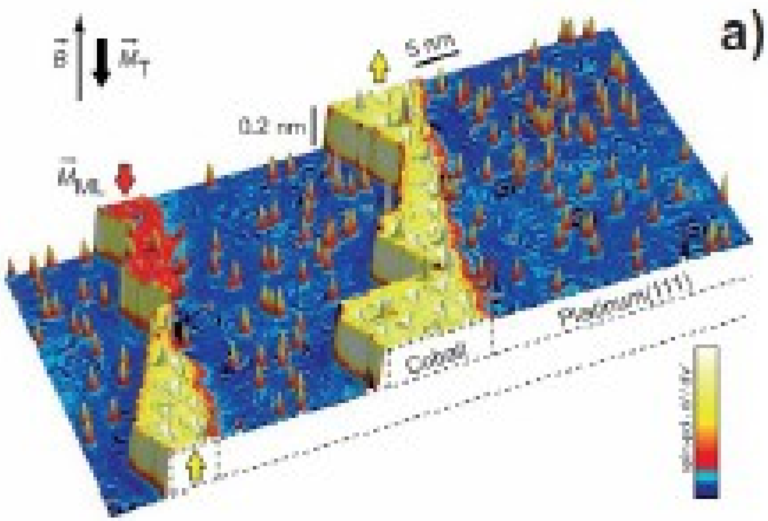
Single Co atoms on Pt



Brune H. et al., P. Surf. Sci, **603**,1812 (2009)

Ordering properties

Co atoms on Pt(111)

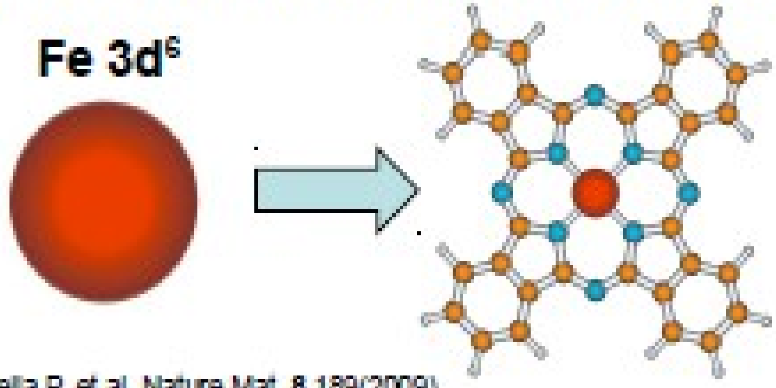


[1] Meier,F. et al., Science 320, 82-6 (2008).

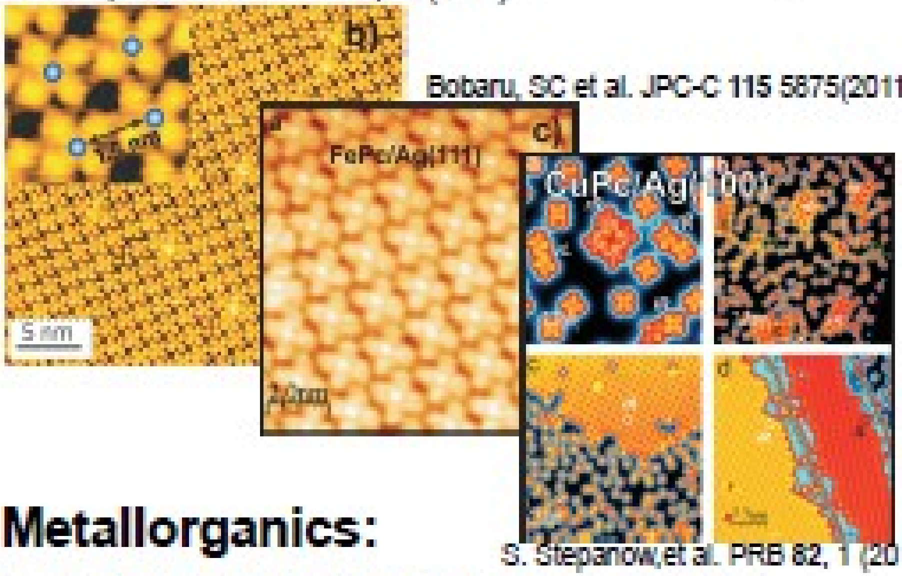
Single atoms:

- Difficult to order
- Strong interaction with substrate
- Cluster formation
- How to control the electronic properties?

Embedding in a organic matrix: Metallorganics



Gambardella,P. et al. Nature Mat. 8,189(2009).



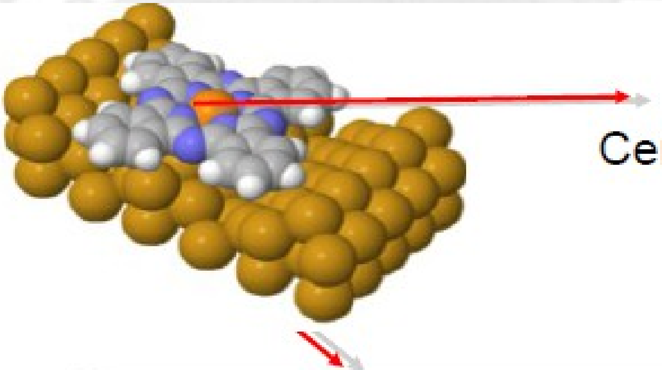
Bobaru, SC et al. JPC-C 115 5875(2011).

S. Stepanow,et al. PRB 82, 1 (2010).

Metallorganics:

- Highly ordered self-assembly
- Chemical control of organic ligand

Organometallic Molecules:



Central magnetic atom

Self-assembly

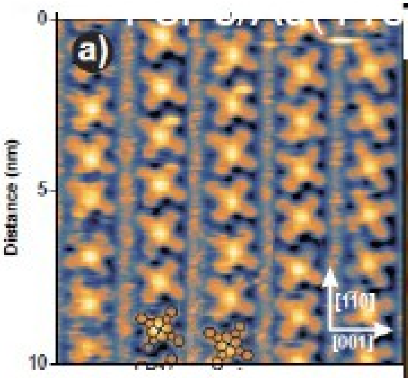
Spontaneous assembly of molecules into structured aggregates under equilibrium.

Whitesides GM *et al.*, Science **254,** 1312(1991)

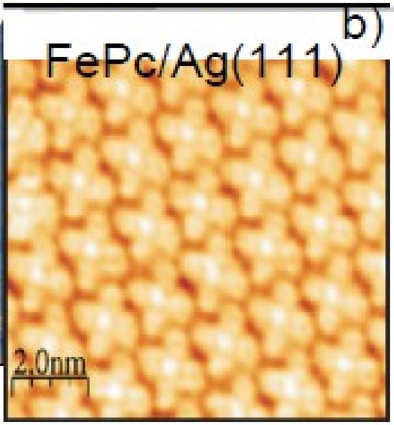
2D ordered structure: Spin Network

M.G. Betti et al., Langmuir

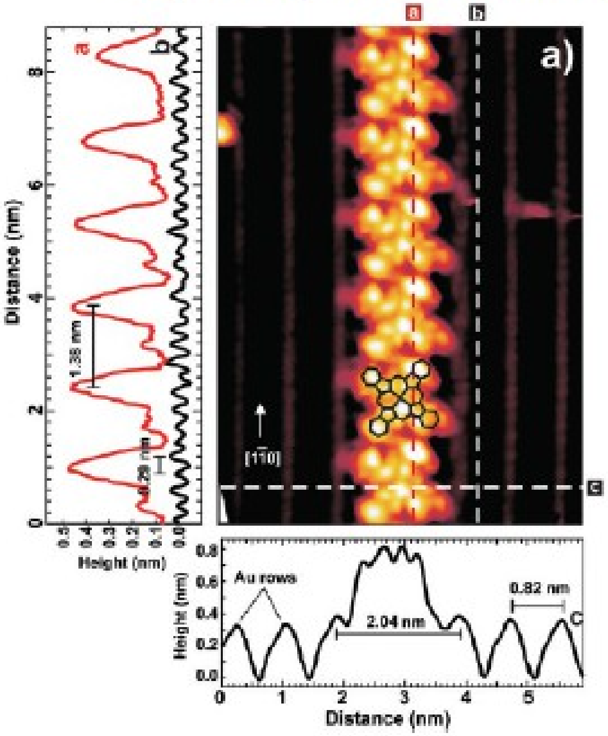
28 (37), 13232-13240 (2012)



Bobaru, SC et al. JPC-C **115** 5875(2011

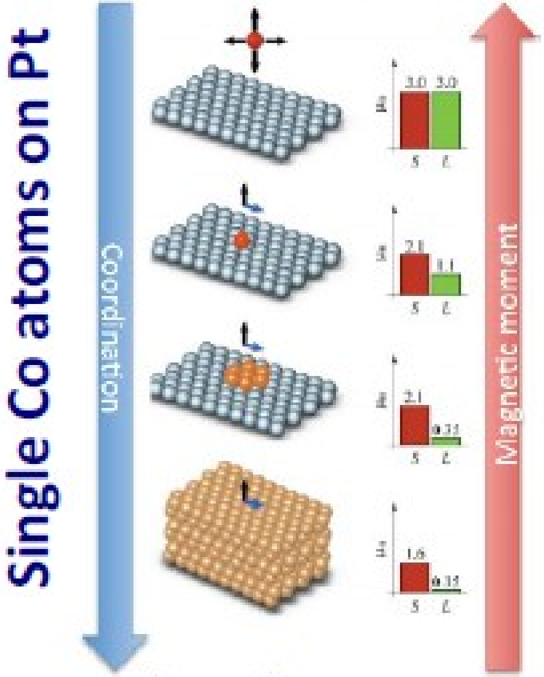


Organic part: "anchoring effect"



Fortuna et al., J. Phys. *Chem. C.* **116**, 6265 (2012)

Bare atoms approach



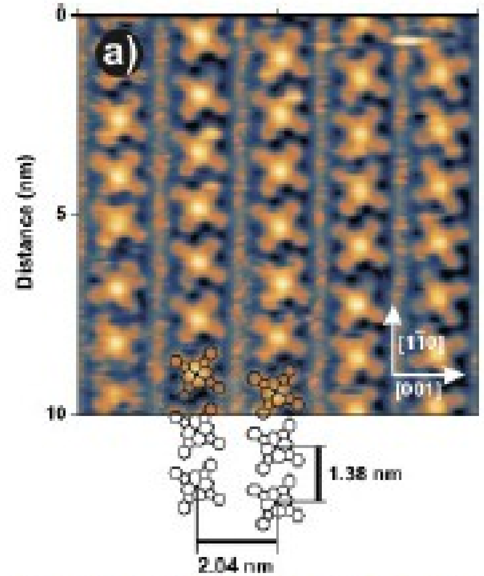
Brune H. et al., P. Surf. Sci, **603**,1812 (2009)

- **High magnetic anisotropy than isolated atom;**
- **High magnetic moment;**

BUT:

- **Lack of thermal stability**
- **Clustering ——► Quenching**

Molecules on metals



Betti et al., Langmuir, **28**, 13232 (2012)

- **High thermal stability**
- **No clustering**

BUT:

- **Quenched magnetic moments**

Betti et al., submitted to Phys. Rev. B

Molecules on Graphene

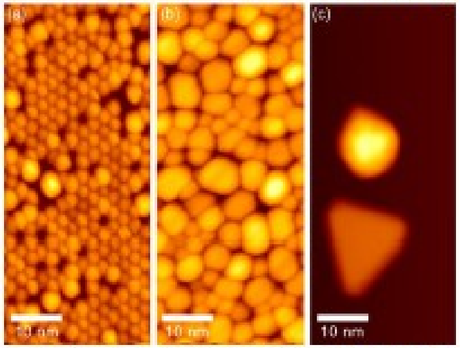
ordered?

Metal substrate decoupling?

Quenching?

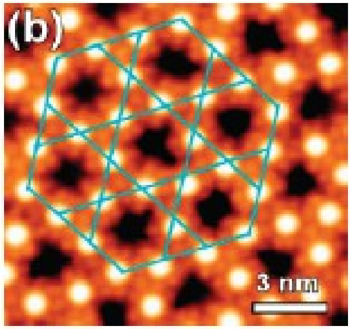
Why FePc?

Bare metal atoms (Co/Gr/Ir)



Vo Van et al. Appl. Phys. Lett. 99, 142504 (2011)

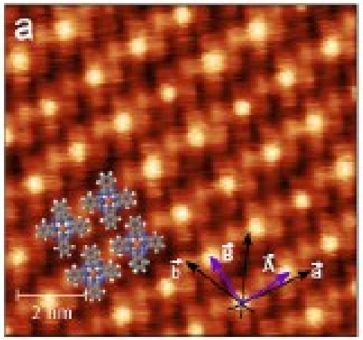
ordered lattices



FePc/Gr/Ru

Mao et al., *JACS*. 131, 14136 (2009)

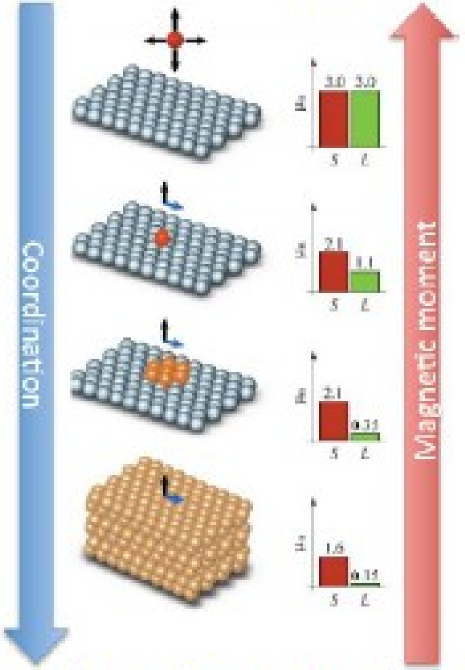
CoPc/Gr/Ir



Hamalainen et al., *J. Phys. Chem. C, in press*

Bare atoms approach

Single Co atoms on Pt



Brune H. et al., P. Surf. Sci, 603,1812 (2009)

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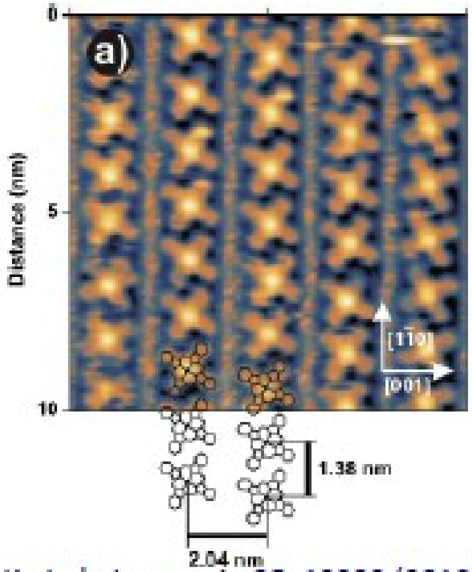

Betti et al., Langmuir, 28, 13232 (2012)

- High thermal stability
- No clustering

BUT:

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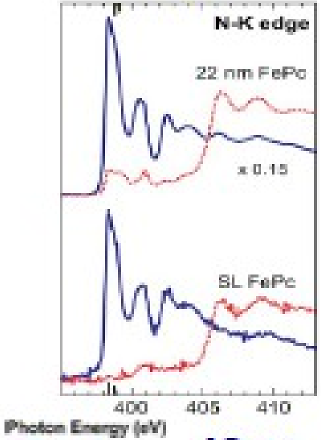
Molecules on Graphene

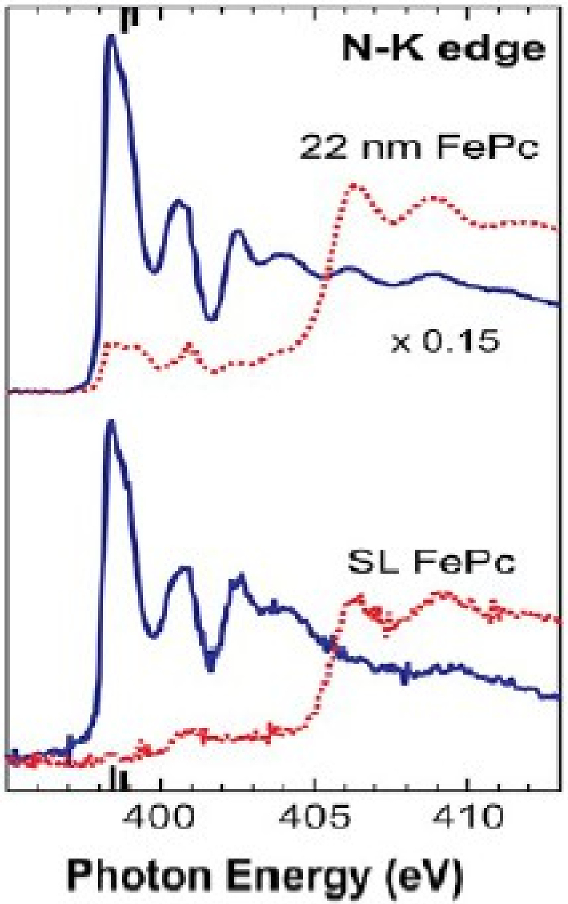


Ordered? Yes!

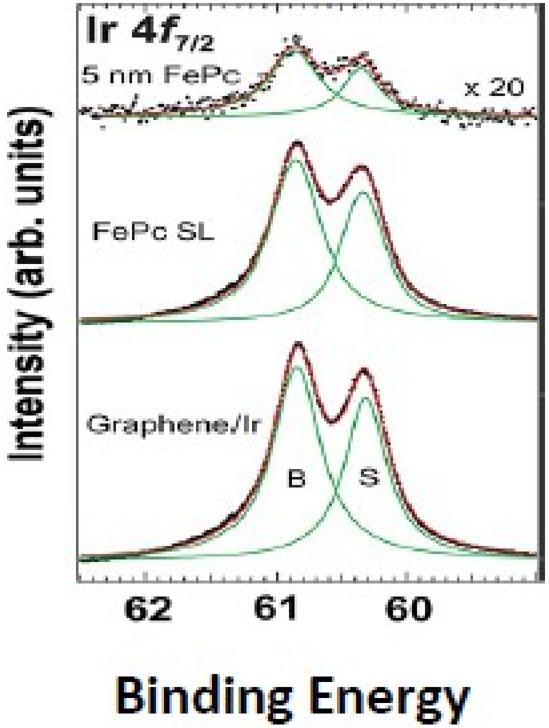
Decoupled? Yes!

Quenching?

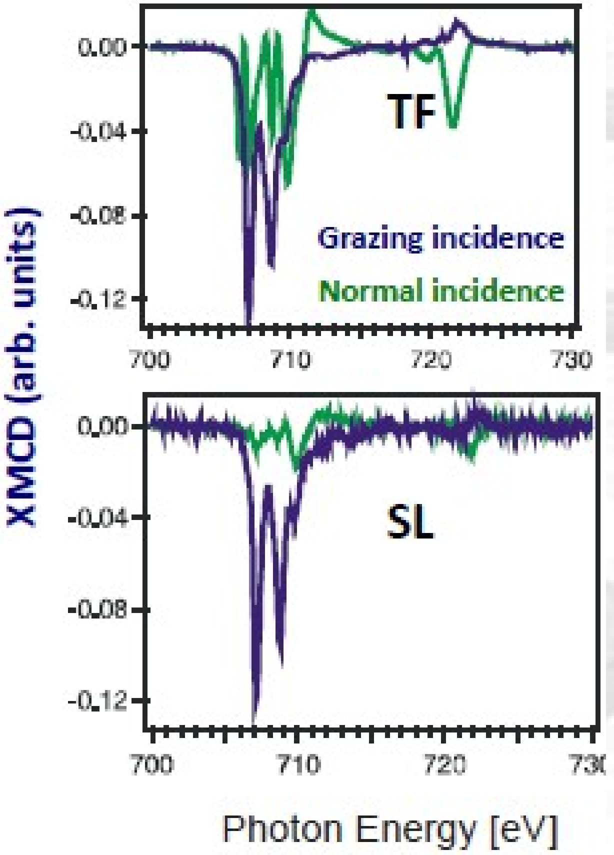
Molecules grow flat preserving graphene



Molecules decoupled from metal

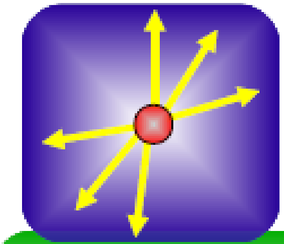


Enhanced magnetic anisotropy

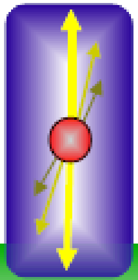


The role of Graphene/Ir(111) and FePc

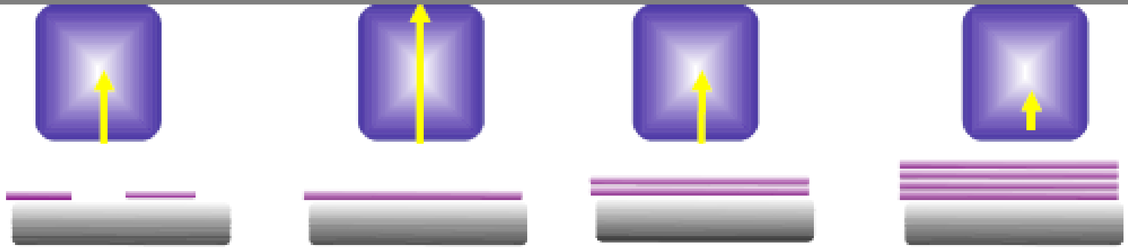
- Non-quenching of the magnetic properties



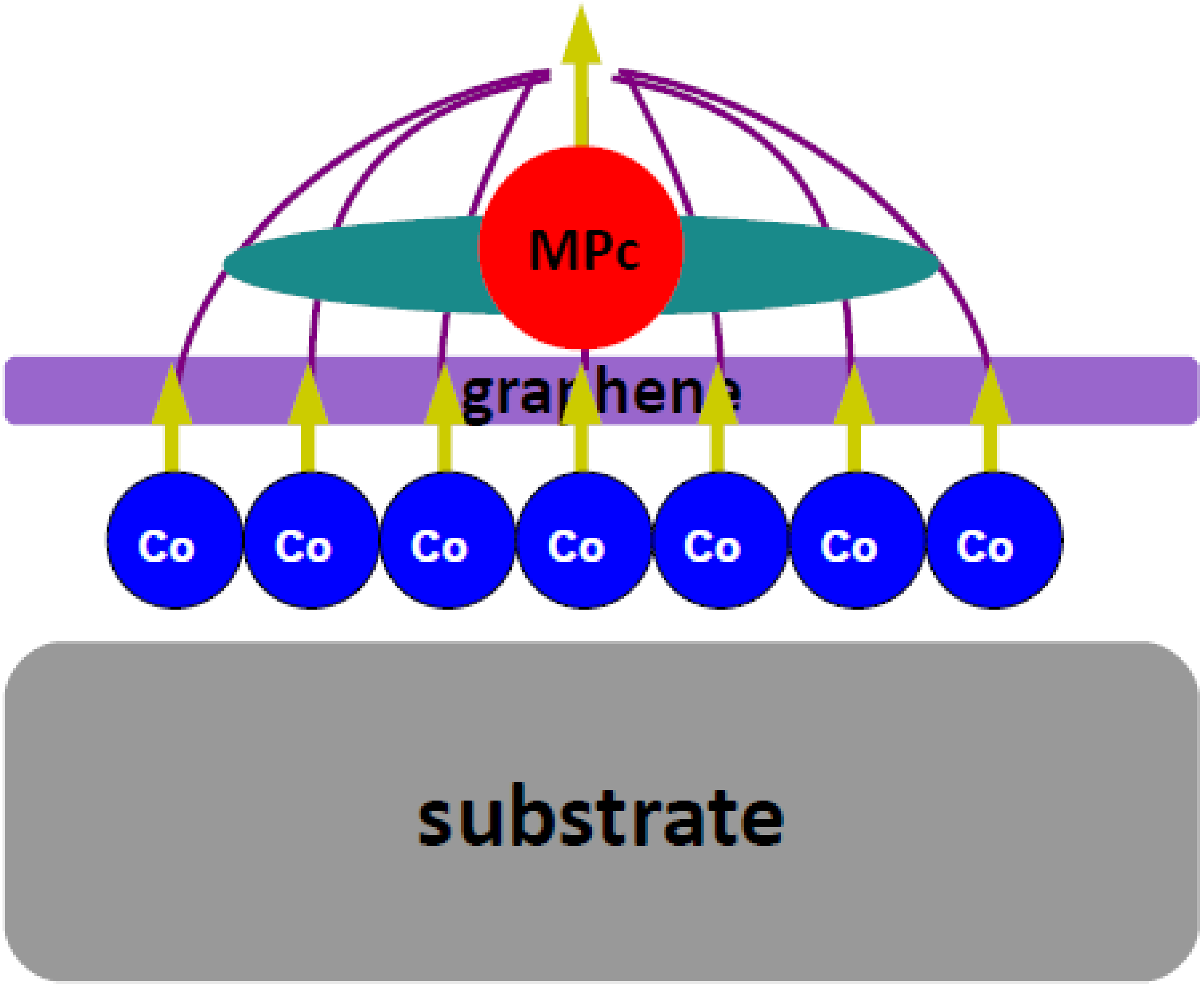
  - Enhanced anisotropy -->
  - → increased correlation



- Intriguing behaviour as a function of FePc thickness



Co intralayer on supported Gr



Enhancing anisotropy exploiting the interaction

Graphene for energy

Lithium battery

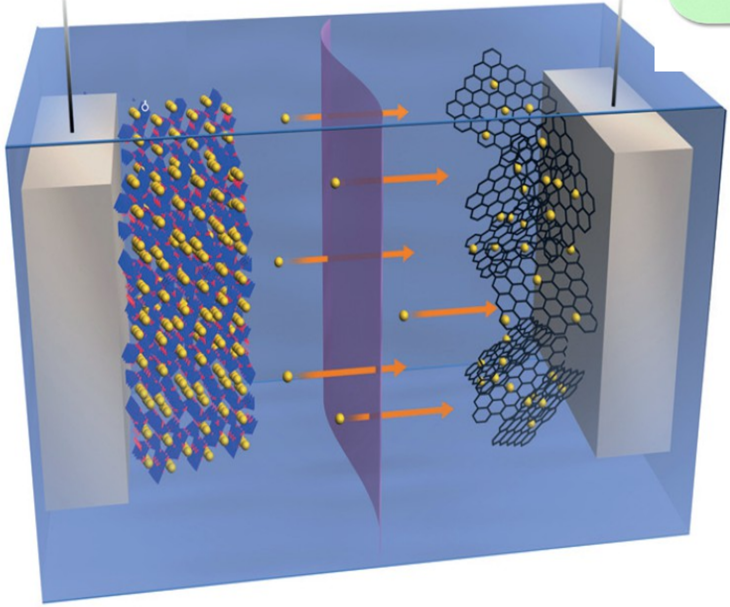
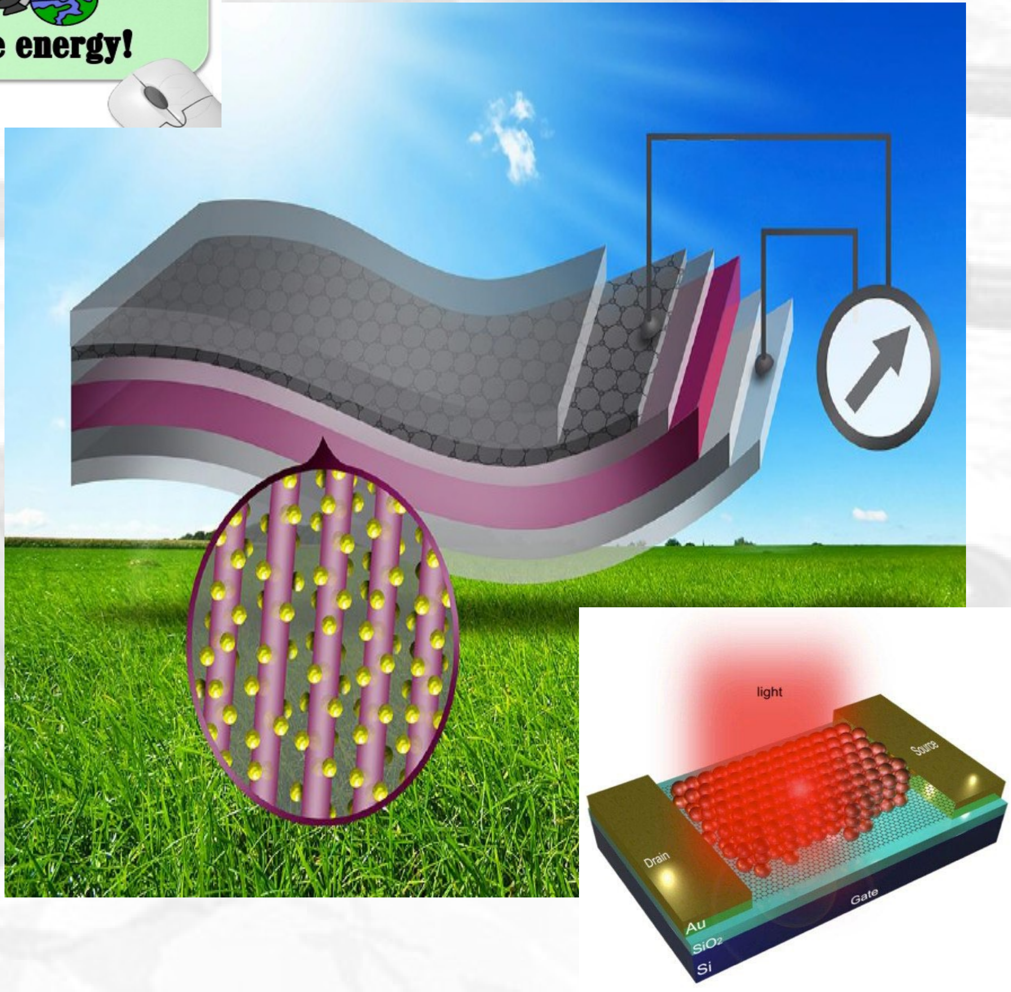


Figure 1 | A schematic representation of a hybrid battery–capacitor device, in which an intercalation material would be used as the cathode (left) and graphene as the anode material (right). Lithium ions (yellow) are inserted and de-inserted during charge and discharge cycles. Figure reproduced with permission from ref. 16, © 2011 Wiley.

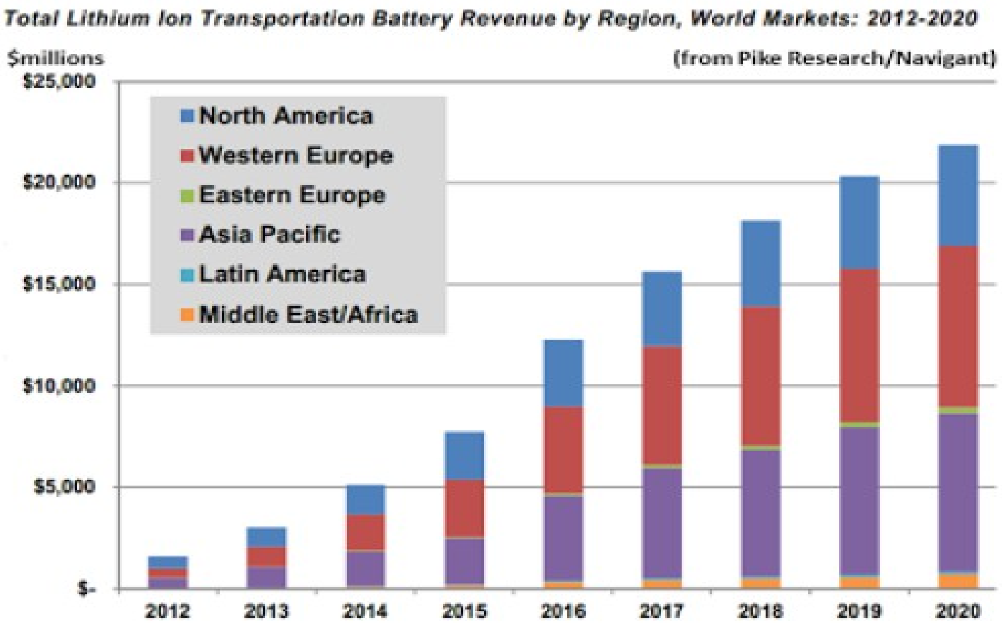
Solar cell



Graphene for lithium batteries

Li-ion batteries

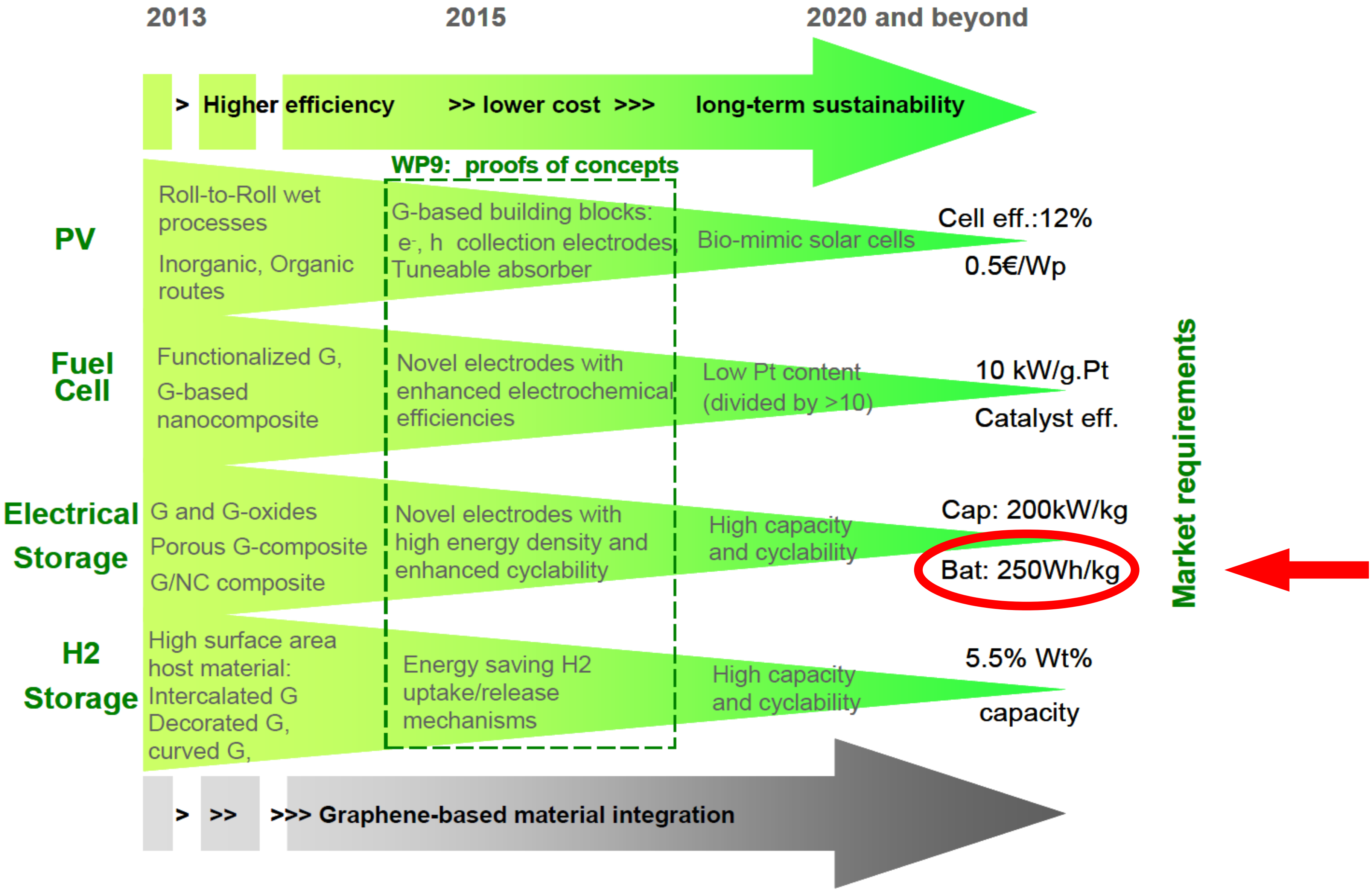
Li-ion Batteries



Total Lithium Ion Transportation Battery Revenue by Region, World Markets: 2012-2020

(from Pike Research/Navigant)

Graphene flagship for Energy: objectives for 2020



2013

2015

2020 and beyond

> Higher efficiency >> lower cost >>> long-term sustainability

WP9: proofs of concepts

PV

Roll-to-Roll wet processes

Inorganic, Organic routes

G-based building blocks:

e^-, h collection electrodes

Tuneable absorber

Bio-mimic solar cells

Cell eff.:12%

0.5€/Wp

Fuel Cell

Functionalized G,

G-based nanocomposite

Novel electrodes with enhanced electrochemical efficiencies

Low Pt content (divided by >10)

10 kW/g.Pt

Catalyst eff.

Electrical Storage

G and G-oxides

Porous G-composite

G/NC composite

Novel electrodes with high energy density and enhanced cyclability

High capacity and cyclability

Cap: 200kW/kg

Bat: 250Wh/kg

H2 Storage

High surface area host material:

Intercalated G

Decorated G,

curved G,

Energy saving H2 uptake/release mechanisms

High capacity and cyclability

5.5% Wt%

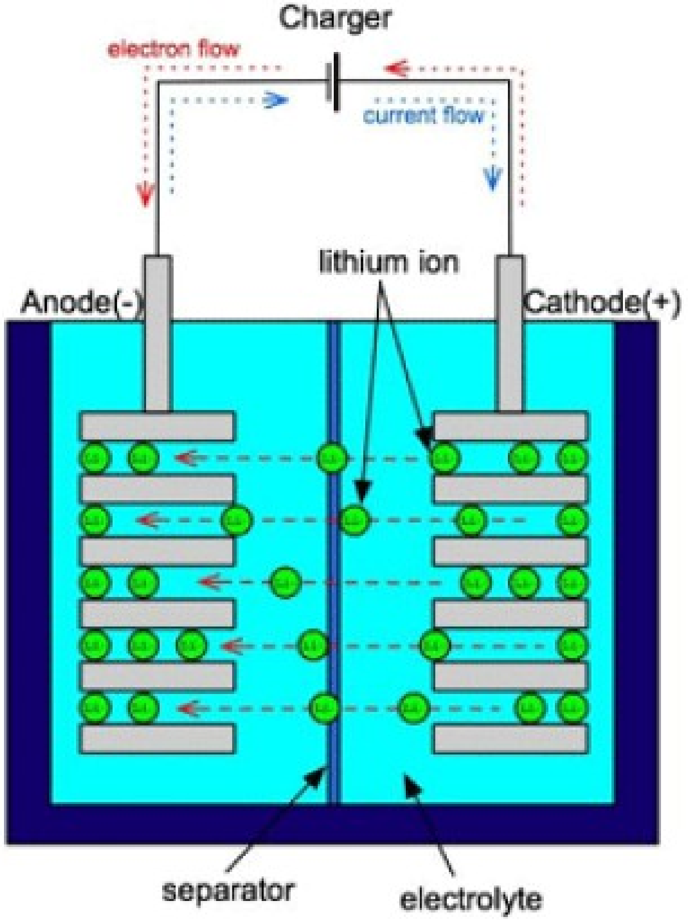
capacity

Market requirements

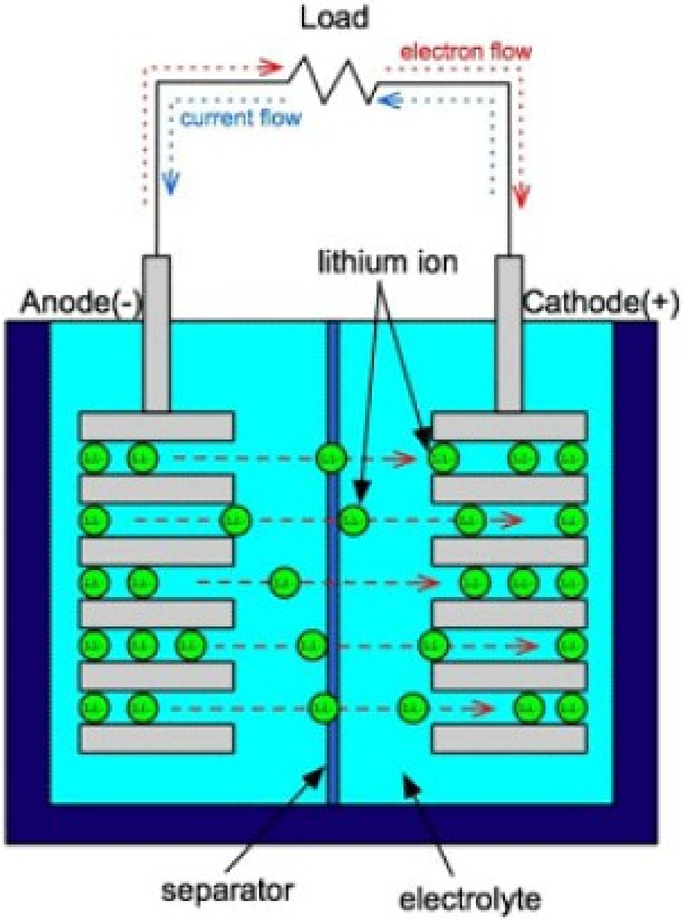
> >> >>> Graphene-based material integration

Figure 1-22: *Graphical representation of progress in WP9. In the figure, G stands for graphene.*

Li-ion batteries

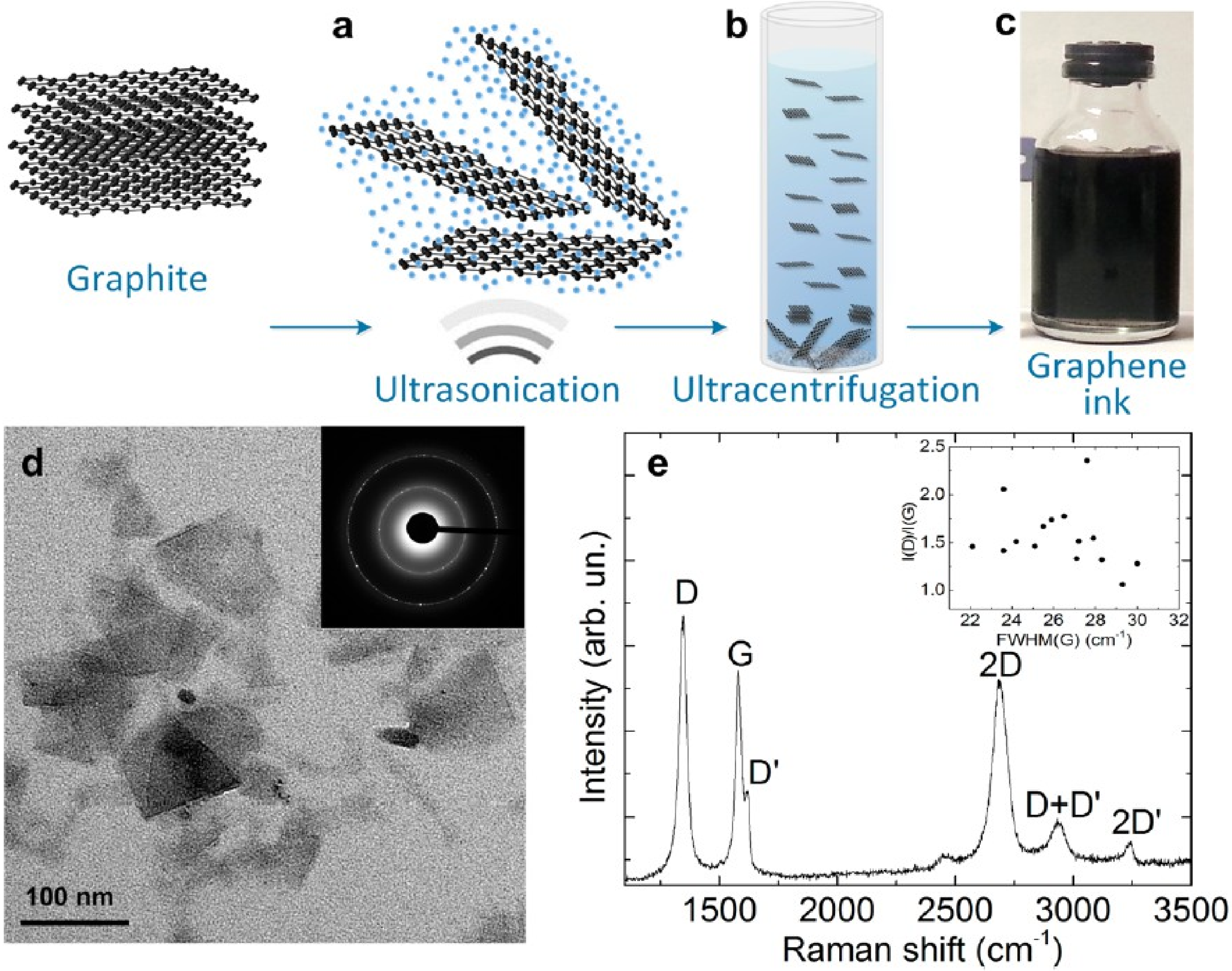


CHARGING



DISCHARGING

Graphene flakes and graphene ink



Li uptake: Graphene more effective than Graphite

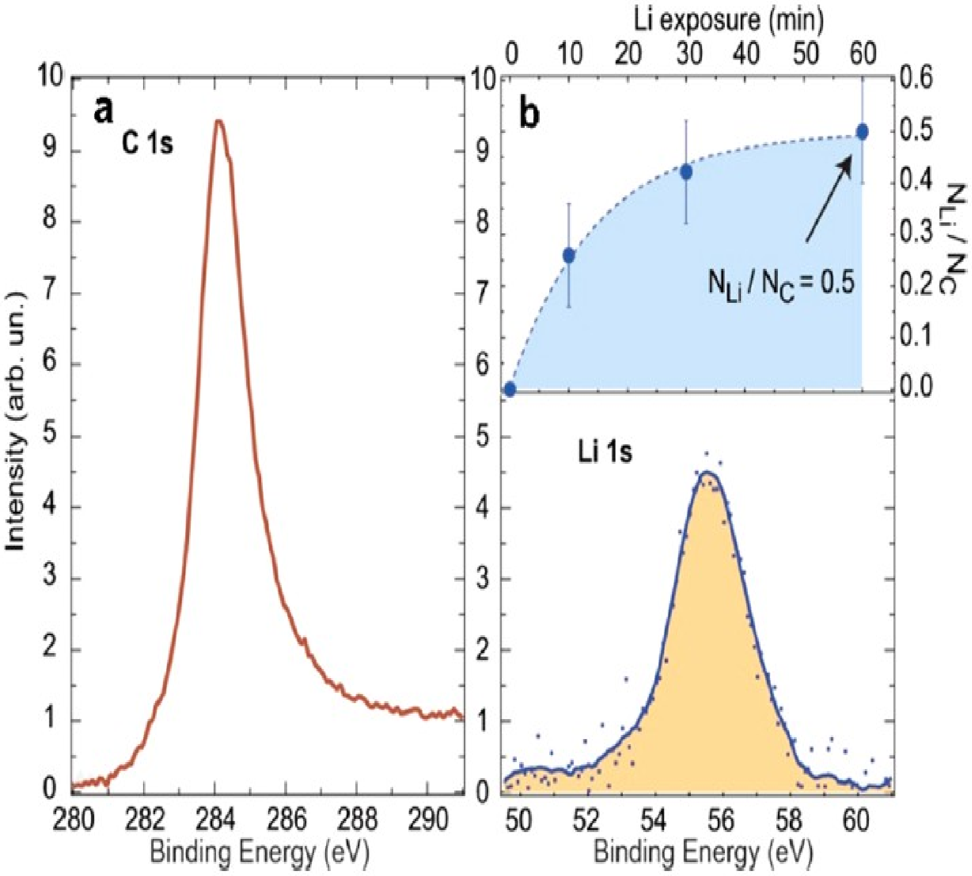


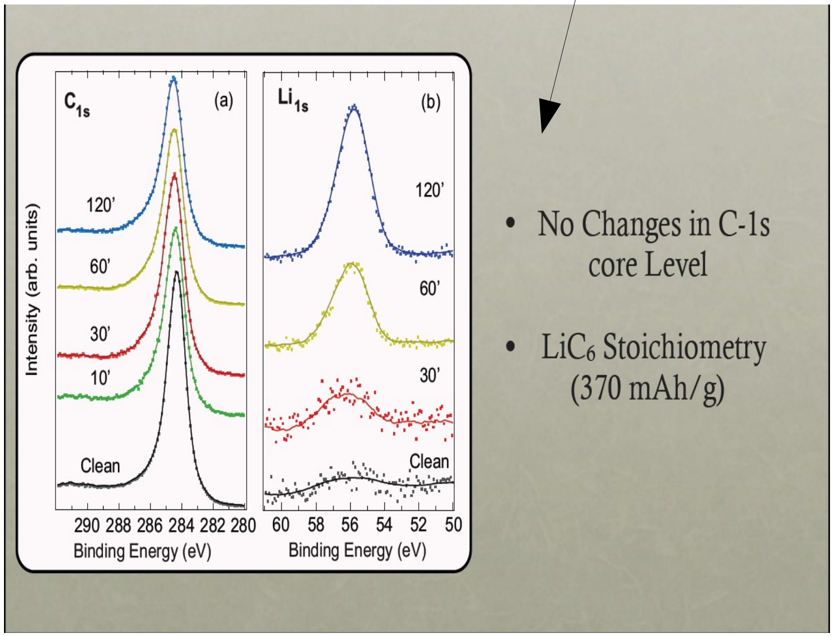
Figure 2. (a) XPS spectral density of the C 1s core-level. (b) XPS spectral density of the Li 1s core-level (lower panel) and estimated number of Li atoms per C atom (upper panel), obtained through the cross-section weighted intensity ratio of the core-levels.

$N_C / N_{Li} = 2$

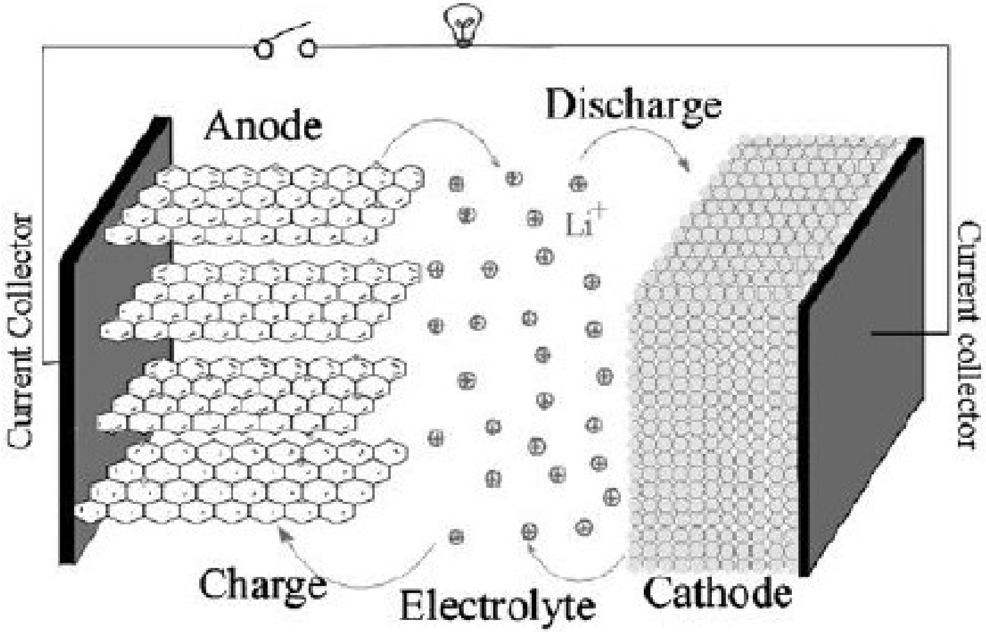
for graphene

$N_C / N_{Li} = 6$

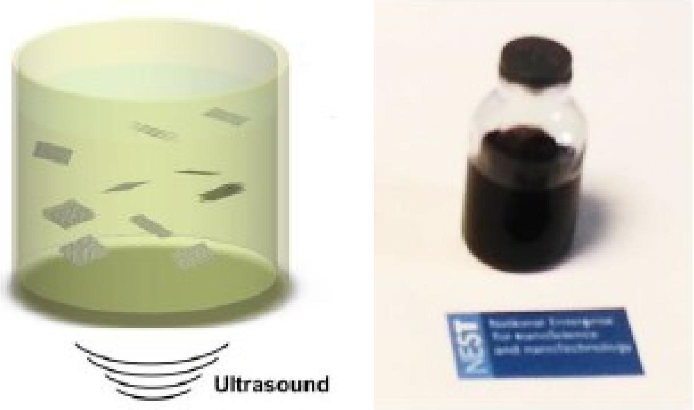
for graphite



- No Changes in C-1s core Level
- LiC_6 Stoichiometry (370 mAh/g)

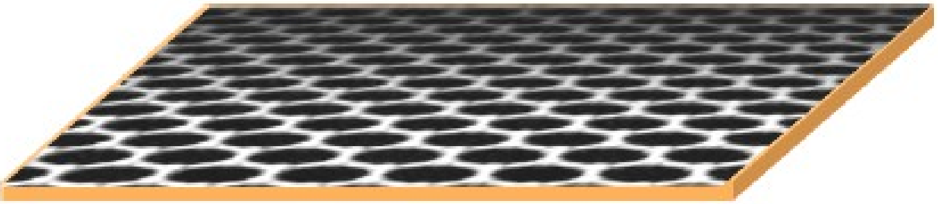


Solution processing

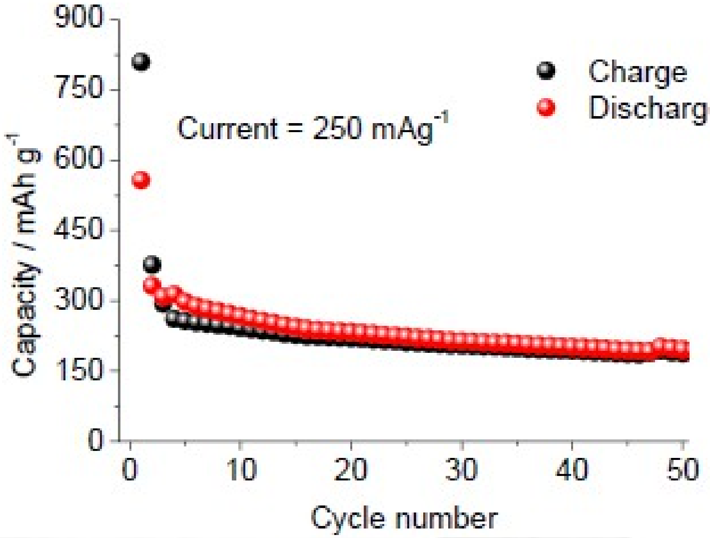


Graphene Ink

Functional electrodes



Deposition of graphene ink on Cu



Graphene flagship for Energy: objectives for 2020

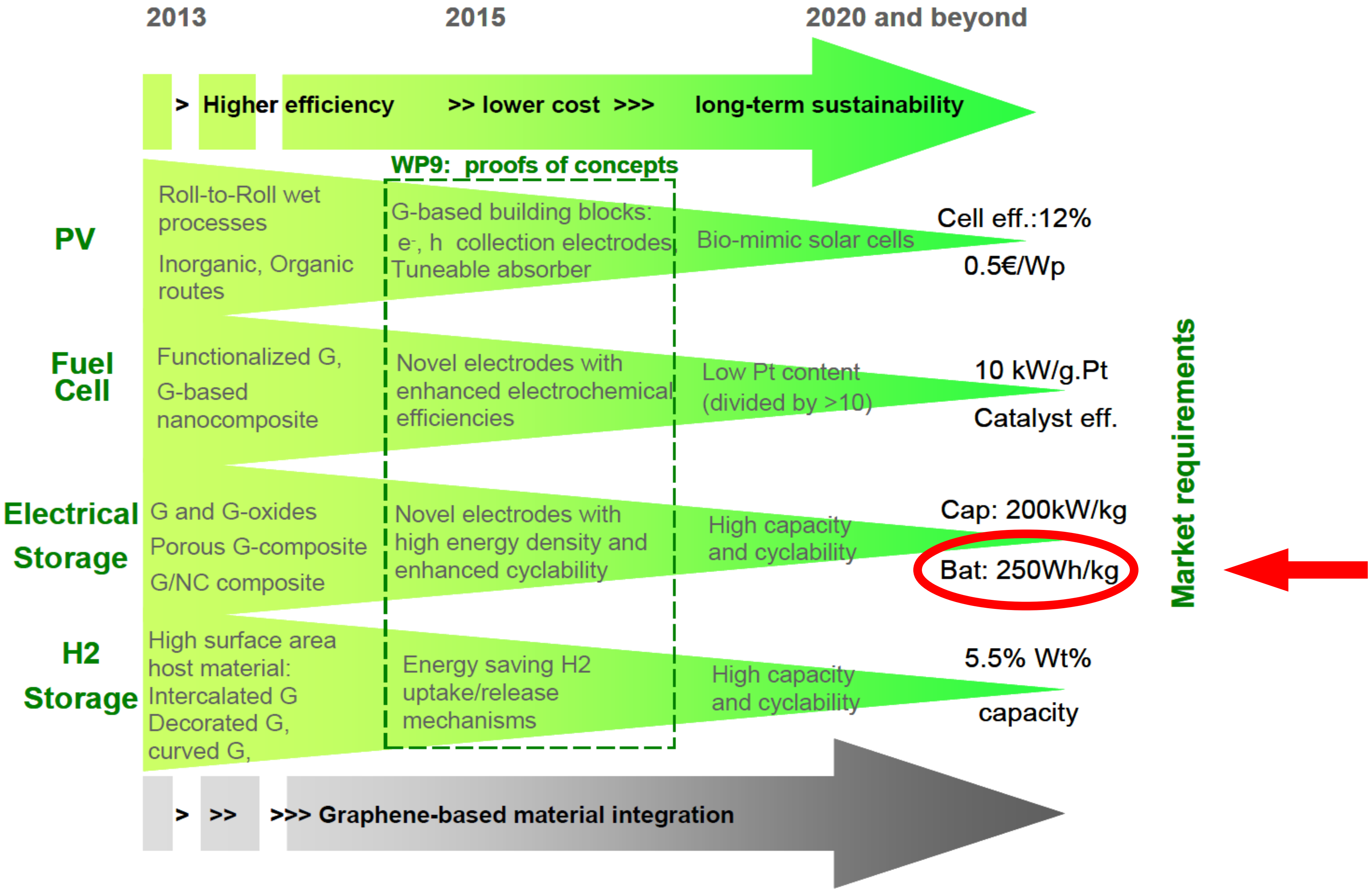


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Figure 1-22: *Graphical representation of progress in WP9. In the figure, G stands for graphene.*

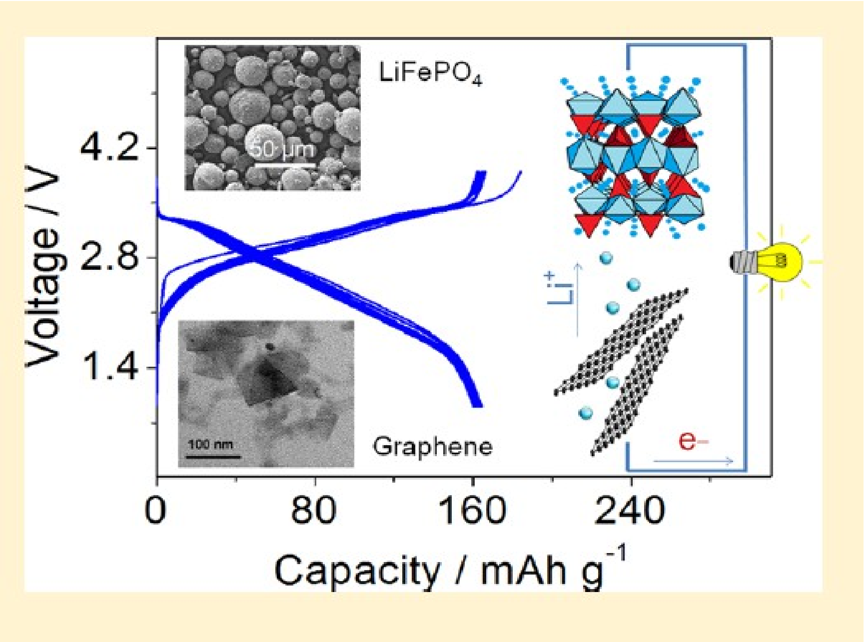
NANO LETTERS

Letter

pubs.acs.org/NanoLett

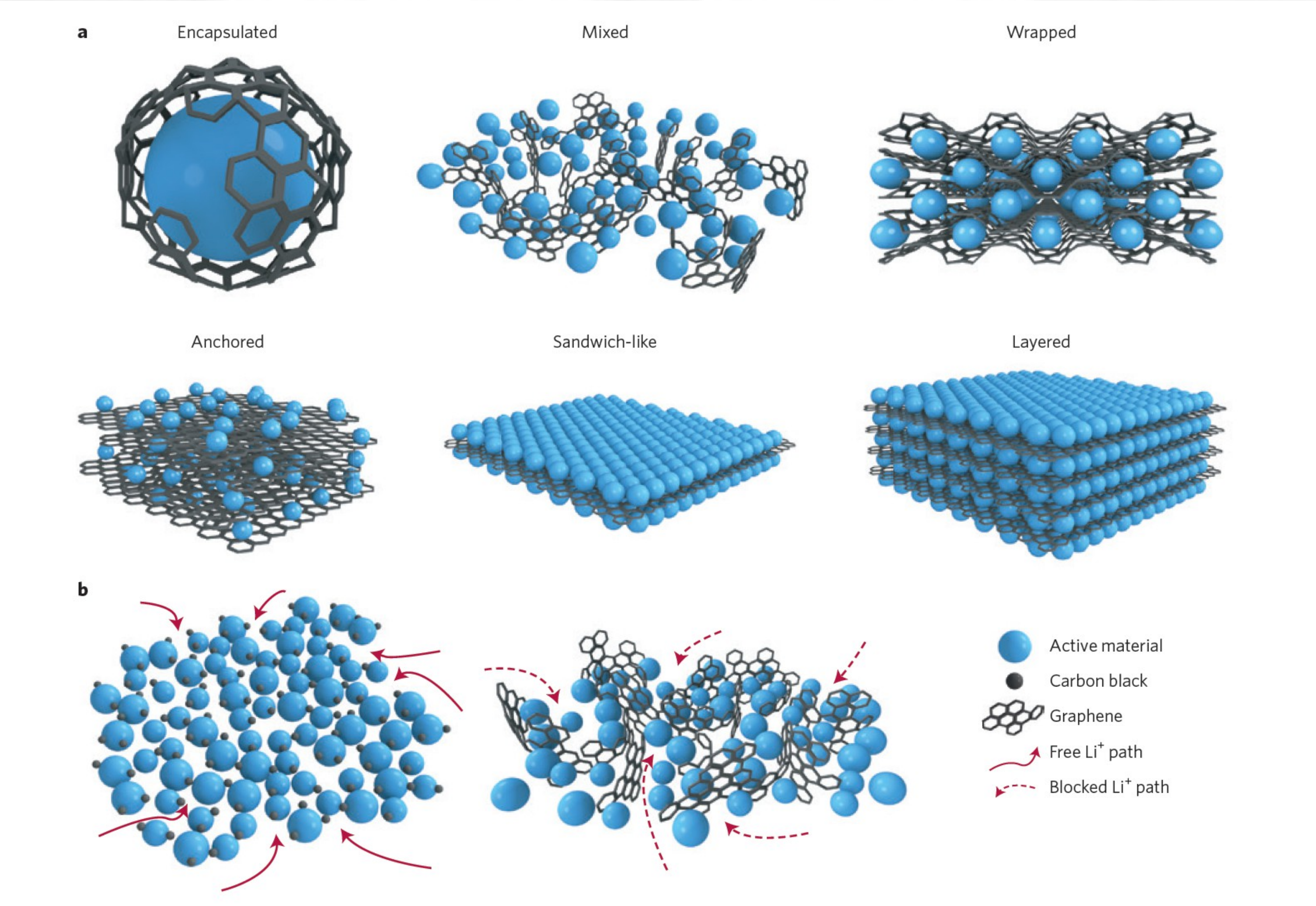
An Advanced Lithium-Ion Battery Based on a Graphene Anode and a Lithium Iron Phosphate Cathode

Jusef Hassoun,[*,†,¶] Francesco Bonaccorso,[*,‡,§,∥,¶] Marco Agostini,[†] Marco Angelucci,[⊥]
Maria Grazia Betti,[⊥] Roberto Cingolani,[‡] Mauro Gemmi,[#] Carlo Mariani,[⊥] Stefania Panero,[†]
Vittorio Pellegrini,[‡,∥] and Bruno Scrosati[*,‡,∇]



Why Li uptake is so effective in graphene?

Edge and defects cannot justify the factor 3,
Packing of the graphene flakes seems to play a crucial role!



New ideas: porous graphene

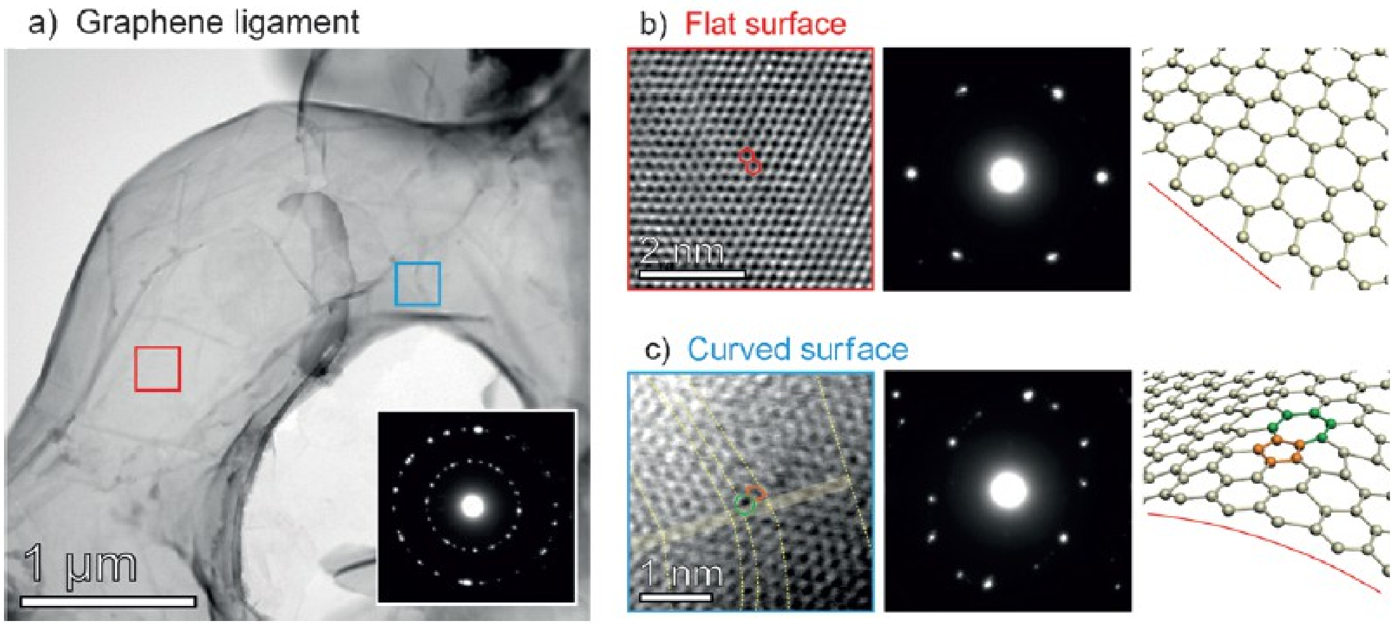


Figure 2. a) Typical low-magnification BF-STEM image of nanoporous graphene. The selected area electron diffraction pattern (inset) shows multiply orientated graphene sheets in the nanoporous configuration. b) HRTEM image and the electron diffraction pattern taken from the flat region of the nanoporous graphene. The atomic structure is consistent with the 2D model. c) The BF-STEM image and the electron diffraction patterns taken from a region with a large curvature gradient. The pentagon–heptagon pair lattices, together with large lattice bending, can be observed. The yellow dashed lines show the lattice directions.

Experimental techniques

Electronic structure: electron spectroscopies

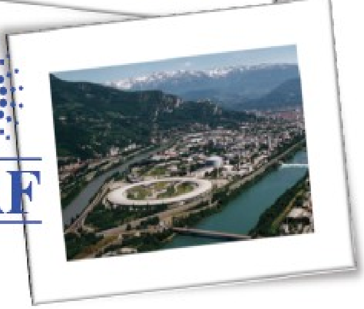
- **Photoemission (in-situ LOTUS Lab. Dip. Fisica Università "La Sapienza"**
- **Polarization dependent X-Ray absorption (Synchrotron radiation: beamlines ID08 @ ESRF ALOISA @ ELETTRA)**
- **X-ray Photoemission (Synchrotron radiation: beamlines CIPO and ALOISA @ ELETTRA)**

Magnetic measurements

- **X-Ray Magnetic Circular Dichroism (Synchrotron radiation + magnetic field: beamline ID08 @ ESRF)**

Structural investigation: microscopy and diffraction

- **Scanning Tunneling Microscopy (STM) in collaboration with Prof. Silvio Modesti TASC Trieste (Synchrotron radiation + magnetic field: beamline ID08 @ ESRF)**
- **Grazing Incidence X-ray Diffraction (Synchrotron radiation: beamline ID03 @ ESRF)**
- **Low Energy Electron Diffraction (LEED) (in situ)**



This work is an effort of …….

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NANORIBBONS Lorenzo Massimi. Oualid Ourdjini, Carlo Mariani

LITHIUM BATTERY Jacopo Chiarinelli, Marco Angelucci (now INFN), Lorenzo Massimi, Carlo Mariani

Collaboration with B. Scrosati, S. Panero, J. Hassoun

N. B. Brookes, V. Sessi
(ID 08 beamline)

ESRF

A. Baraldi, S. Lizzit, R. Larciprete
(SuperESCA beamline)

elettra

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Deborah Prezzi
Elisa Molinari
Daniele Varsano
Stefano Fabris (SISSA-Ts)

ITT V. Pellegrini F. Bonaccorso (graphene ink)

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