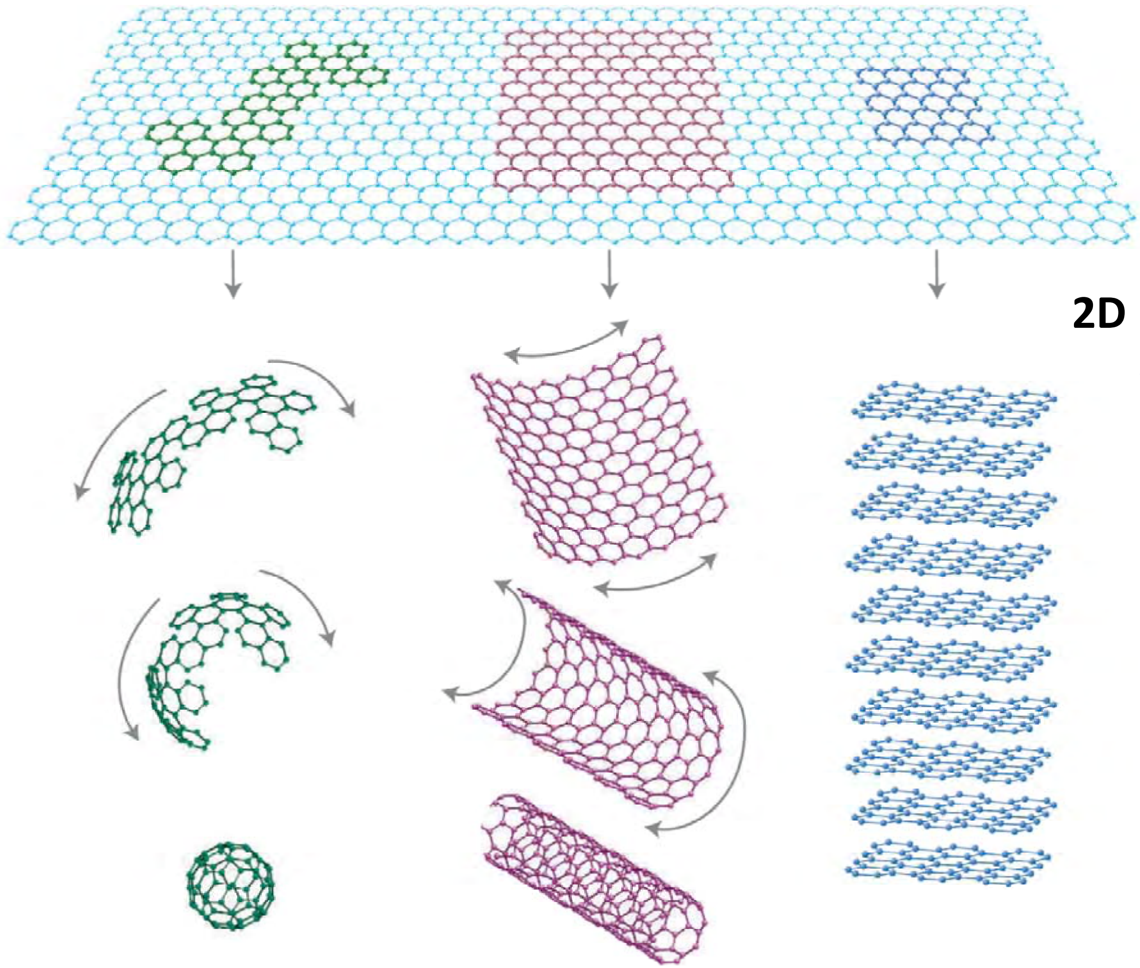
Part II. Introduction of Graphene

Graphene (Mother of all-graphitic form)



2D honeycomb lattice
Graphene

0D
bulky ball

1D
Nanotube

3D
Graphite

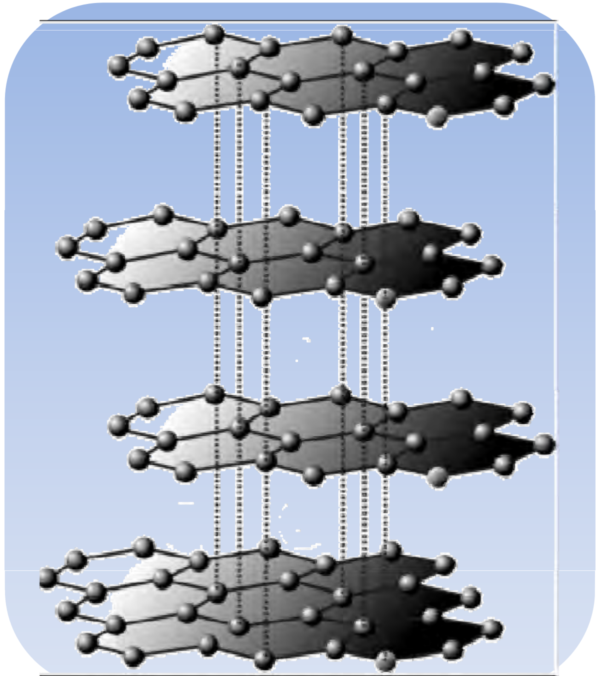
Geims et al, Nature Materials,Vol.6 183, 2007

History of Graphene

- Early: Theoretical description
- 1962: Named by Hanns-Peter Boehm (Graphite + -ene)
- 2004: Single-atom-thick, free-standing graphene is extracted (by Andre Geim and Konstantin Novoselov, Manchester University, U.K.)

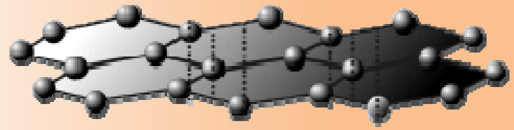
- 2005: Anomalous quantum Hall effect was observed
- 2010: ***Nobel prize in Physics*** for Andre Geim and Konstantin Novoselov
- Now: Stimulate wide researches and be applied to various fields

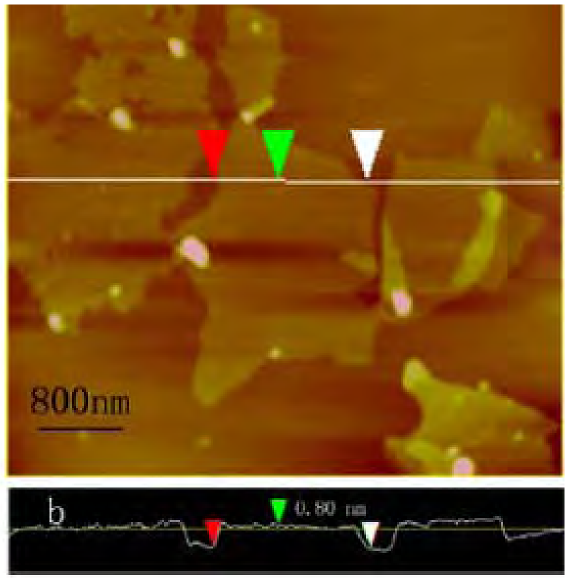
From graphite to graphene



Graphite
Multilayer carbon atom

Graphene
Mono-atomic layer~1nm
(10^{-9} m)





2010 The Nobel Prize in Physics

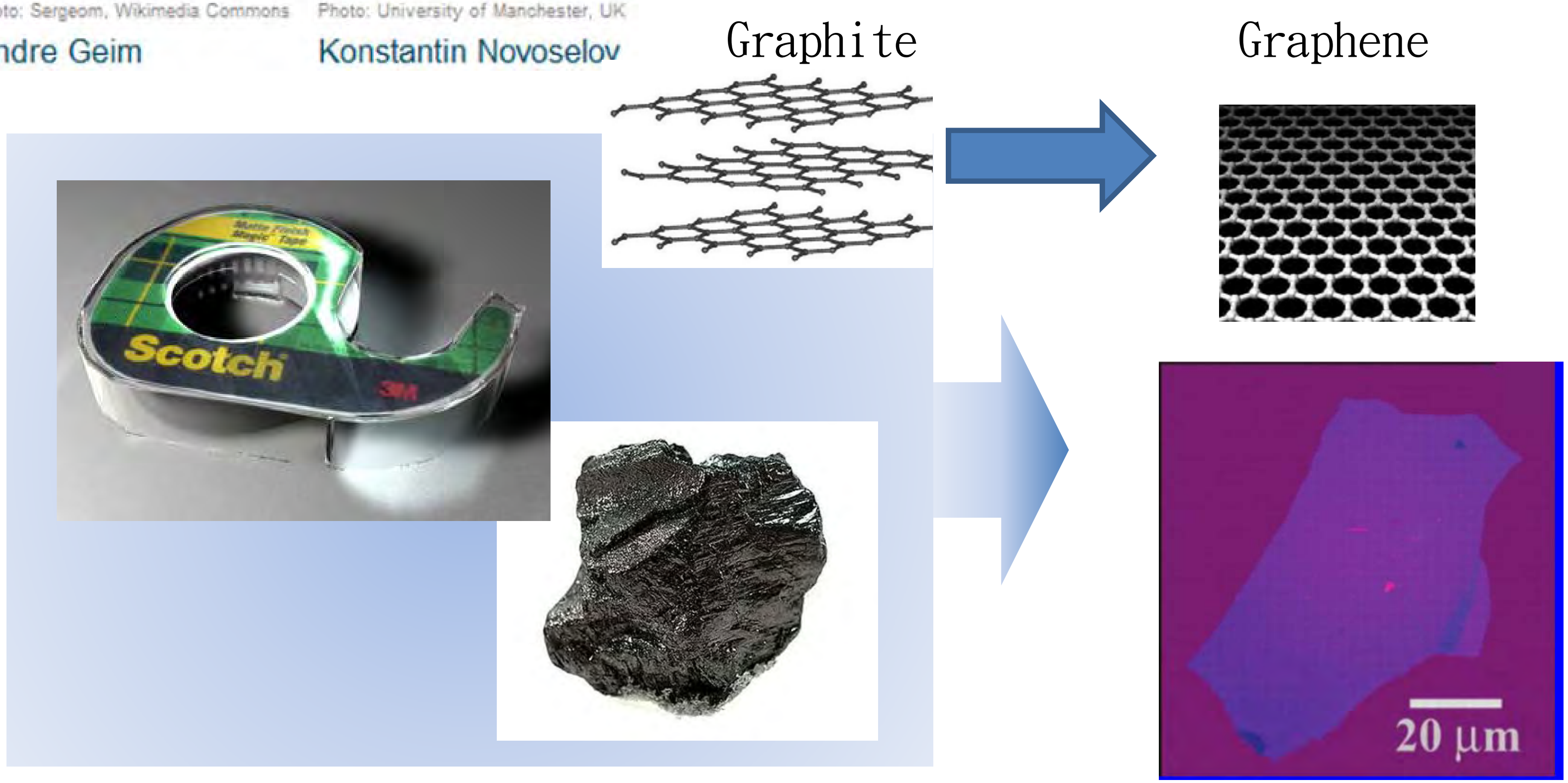
Photo: Sergeom, Wikimedia Commons

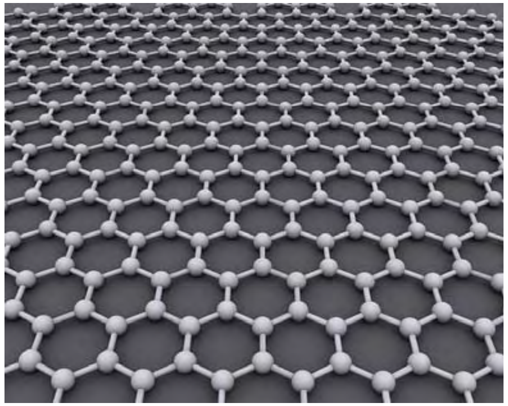
Andre Geim

Photo: University of Manchester, UK

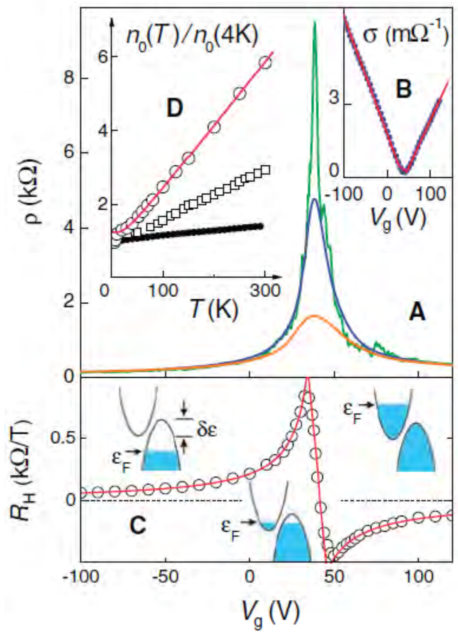
Konstantin Novoselov

Prof. Andre Geim and Konstantin Novoselov at the U. Manchester for groundbreaking experiments regarding the 2-D material graphene



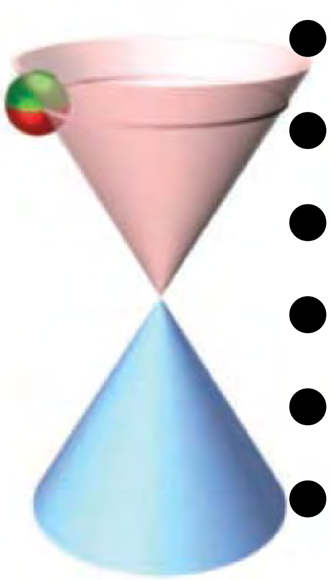


Graphene



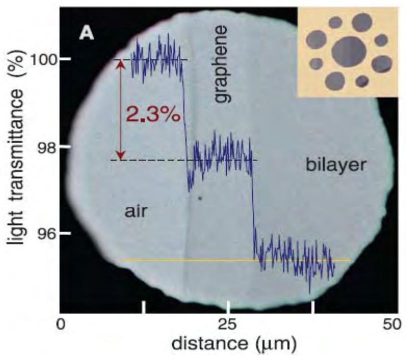
K. S. Novoselov, A. K. Geim. Science (2004)

- **Atomic-thick layer of carbon atom**
- **Zero bandgap**
- **Massless Dirac fermions**
- **High transparency and Flexible**
- **Low Resistivity about 10^{-6} Ω·cm, (< siliver)**
- **Ultrahigh high mobility (1000~300000cm^{2}V^{-1}S^{-1})**
- **etc…**

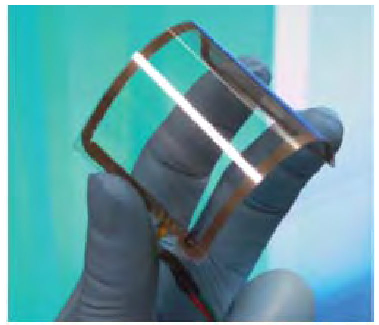


$$\hat{H} = v_F \vec{\sigma} \cdot \hat{p}$$

A. K. Geim, Science (2009)



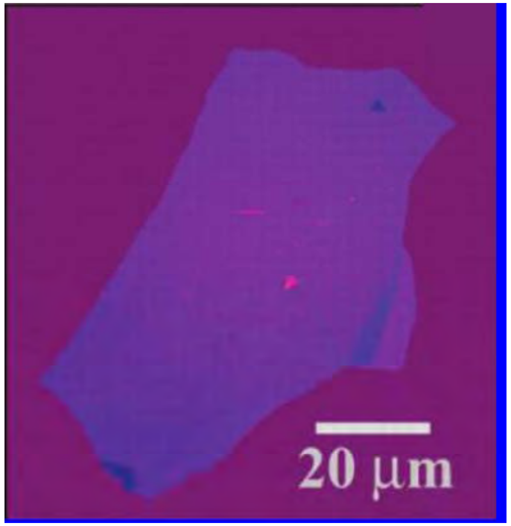
Nair et al., Science, (2008)

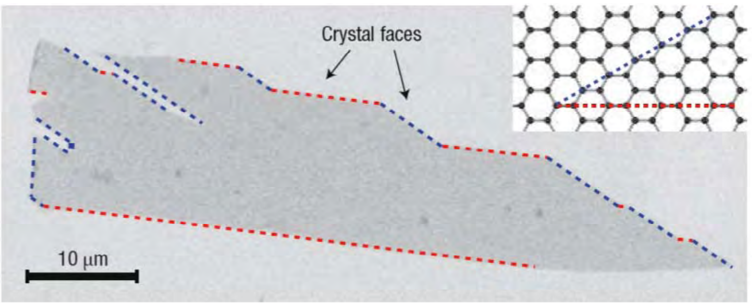


Bae. S *et al.* Nat. Nanotechnol. (2011)

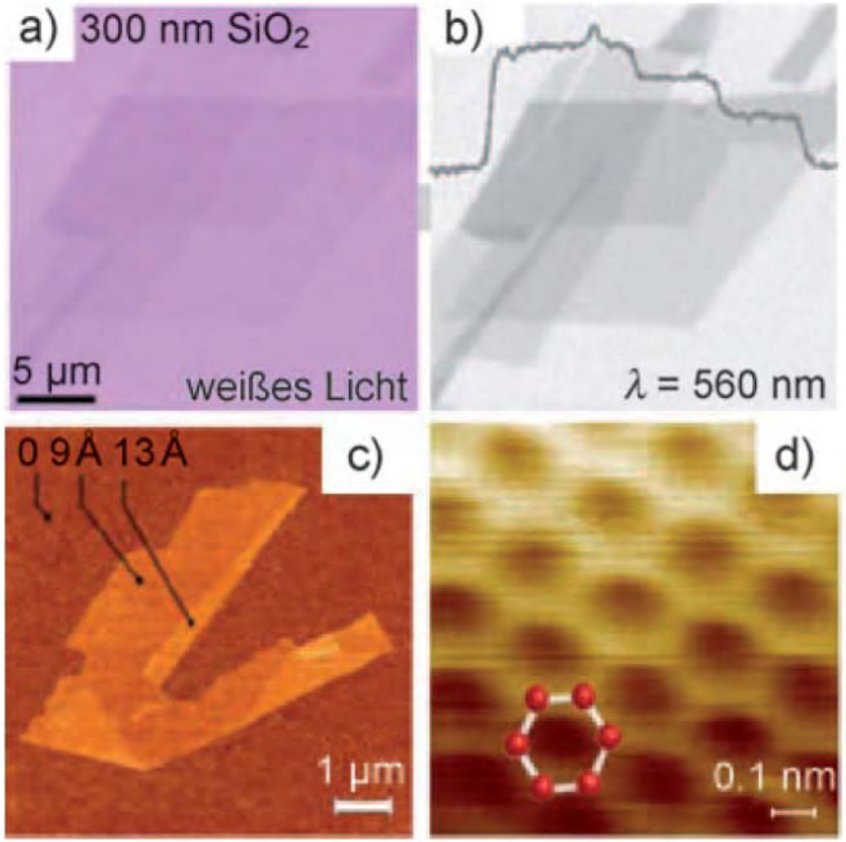
Atomic structure of graphene

- The atomic structure, two-dimensional crystals
- The thinnest Materials





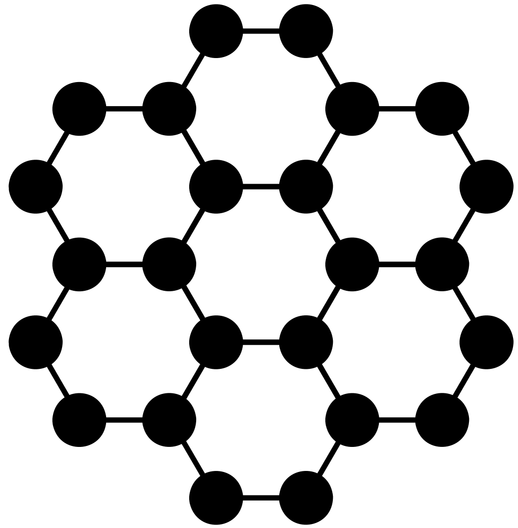
Kraner et al. Chem. Rev. 2010,110,132

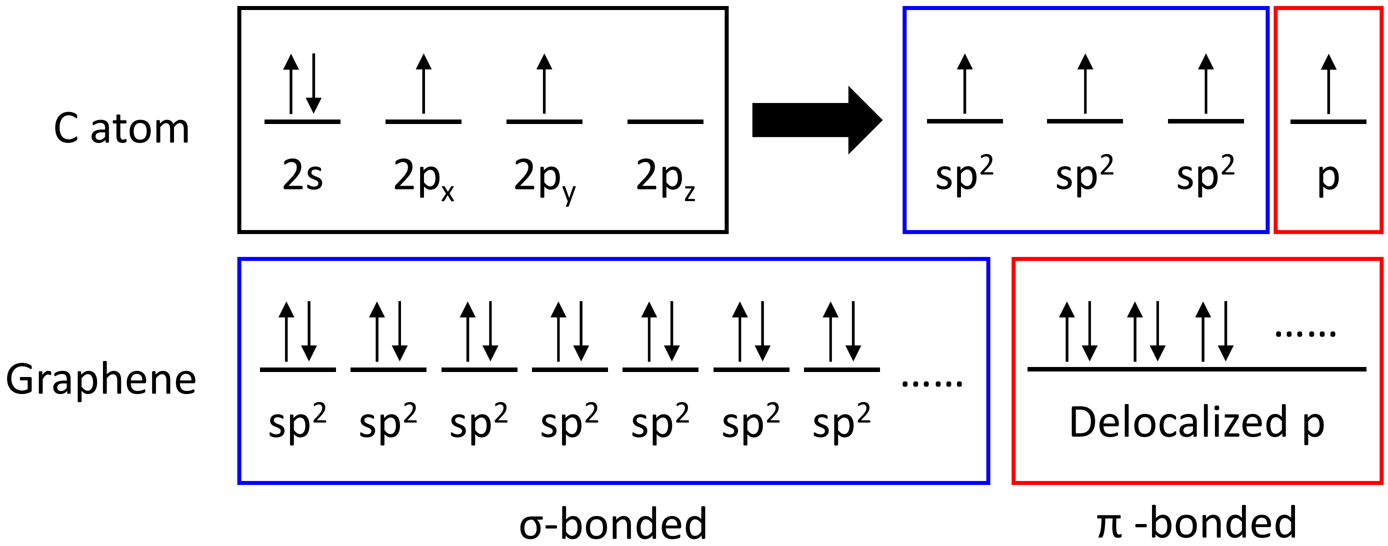


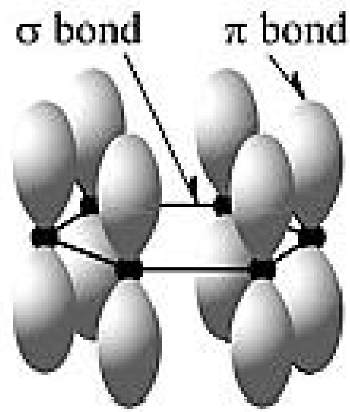
Rao et al, Angew. Chem., 2009,48,7752

Electronic Structure of Graphene

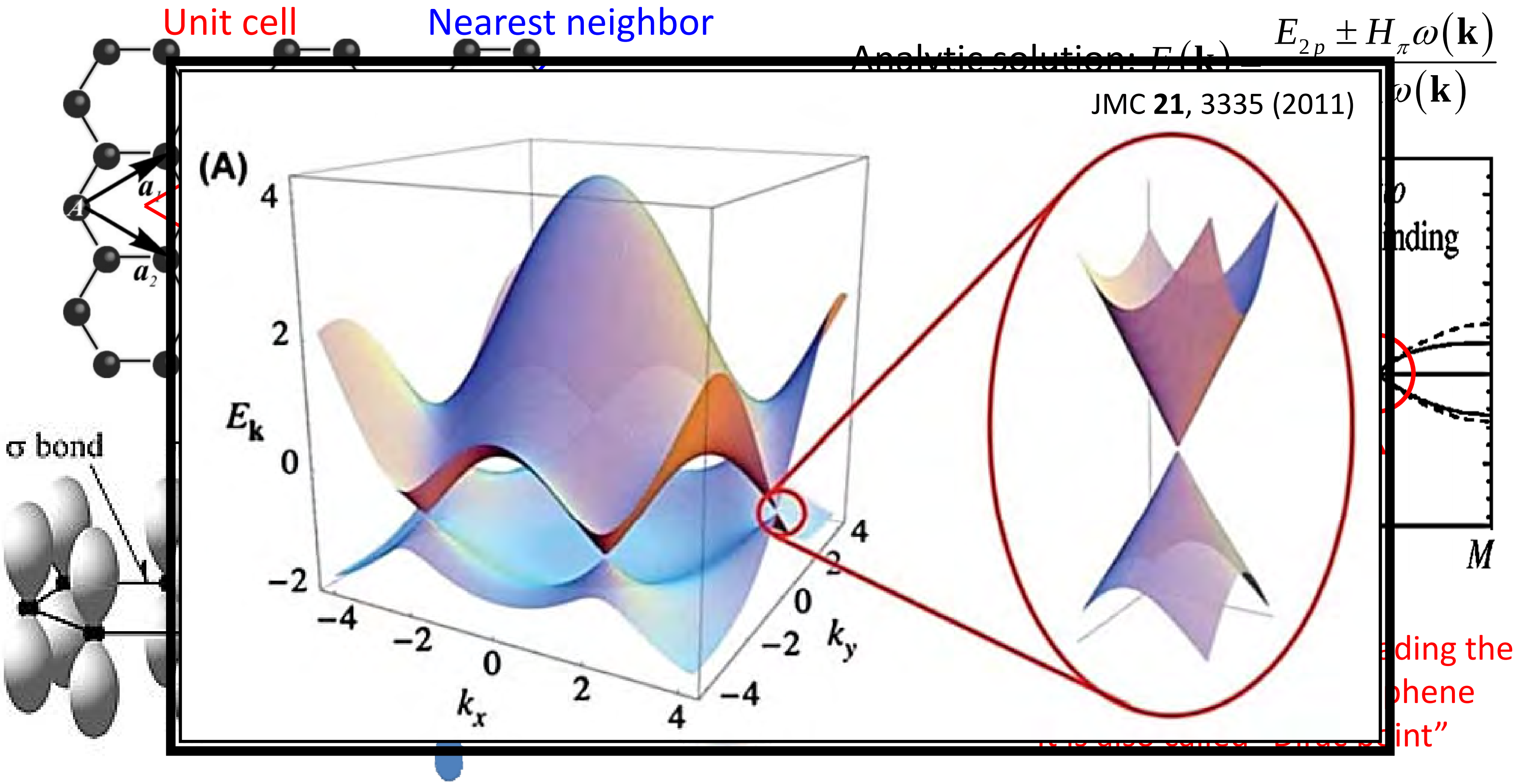
- All C atoms are sp^2-bonded to adjoining C atoms
  - sp^2 electrons form σ bonds
    - Form the honeycomb net of C atoms
  - Delocalized p electrons form π bonds







Tight-binding

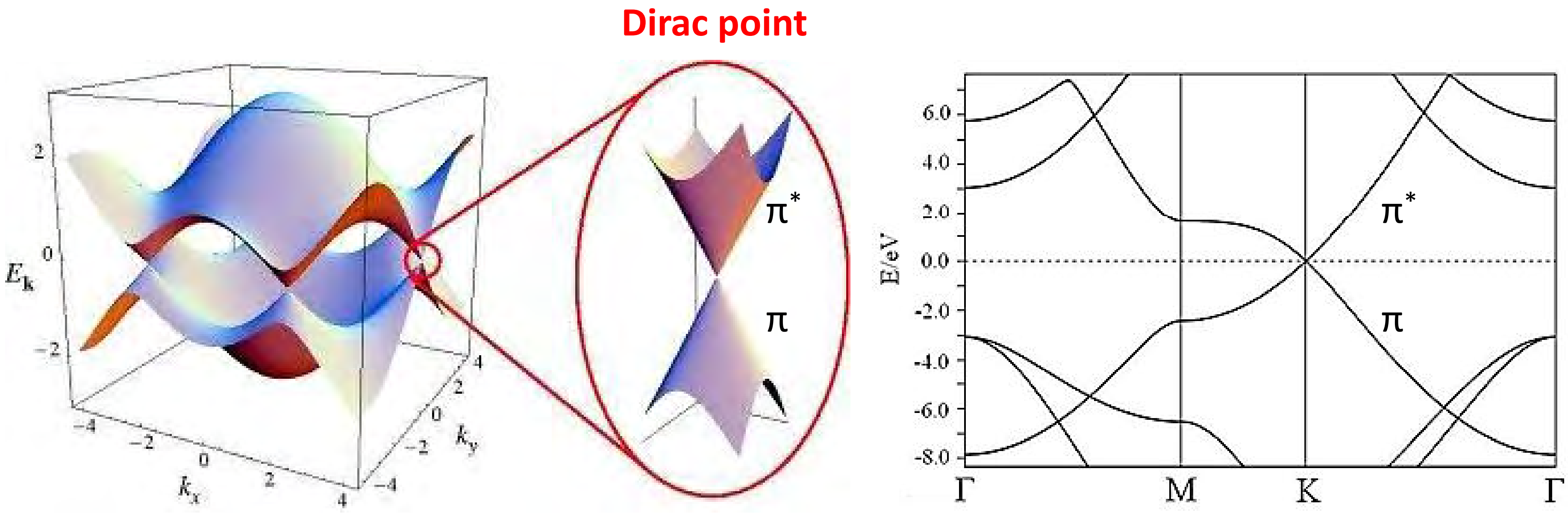


- Bonds with adjacent atoms are most important, therefore the "nearest-neighbor tight-binding description" is usually used

Phys. Rev. B **66**, 035412 (2002)

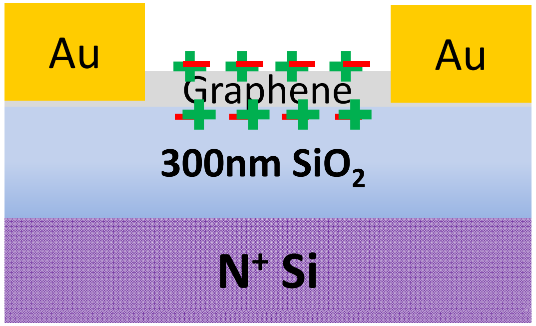
1-2. Fundamental Properties of Graphene

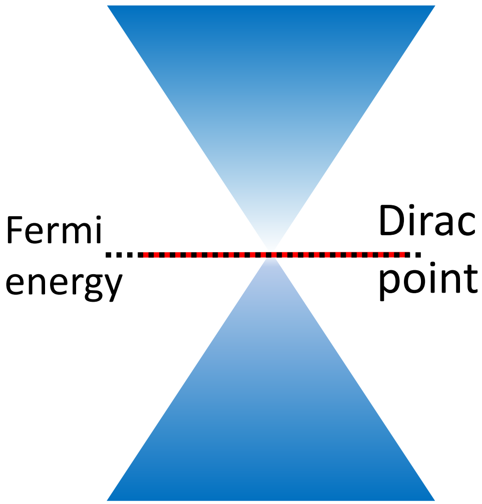
Band Structure of Graphene



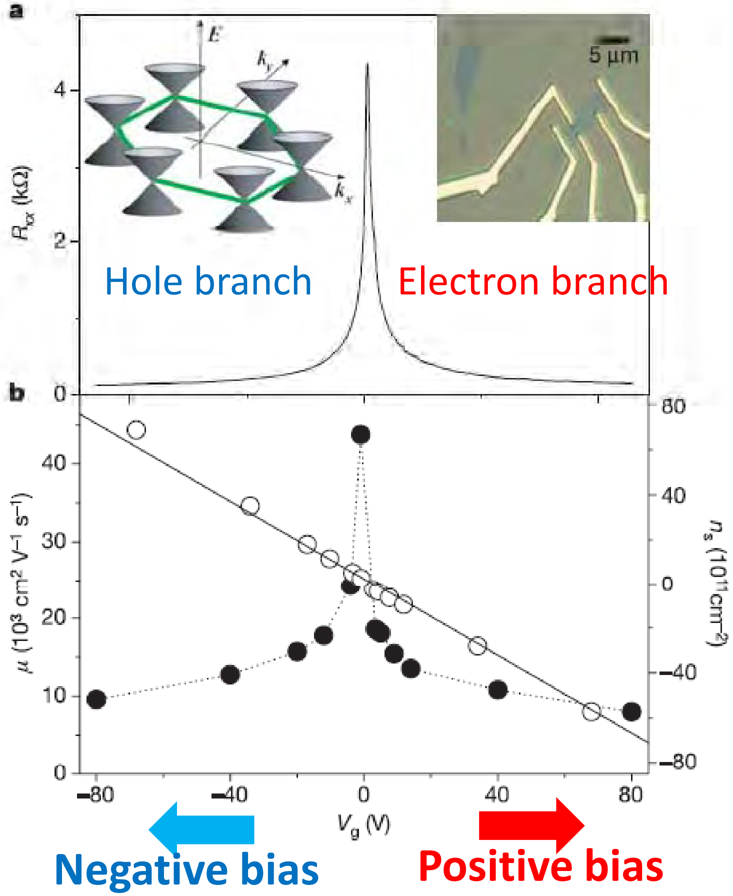
- The valence band and the conduction band meet at Dirac point
  - Metallic behavior
  - "Semi-metal" or "zero-bandgap semiconductor"
- Linear E-k dispersion near Dirac point
  - "Massless" electrons and holes

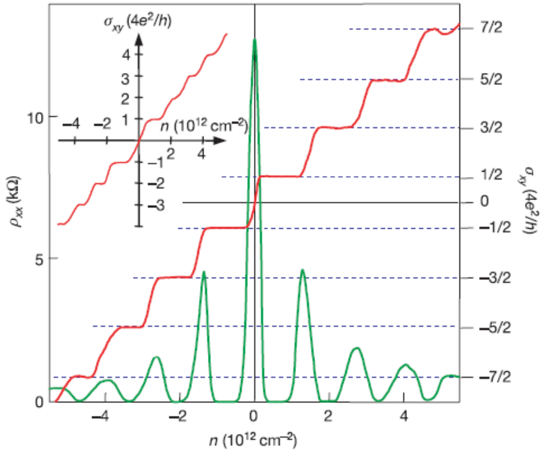
Graphene
Ambipolar transport





Yuanbo Zhang, et al., Nature(2005)





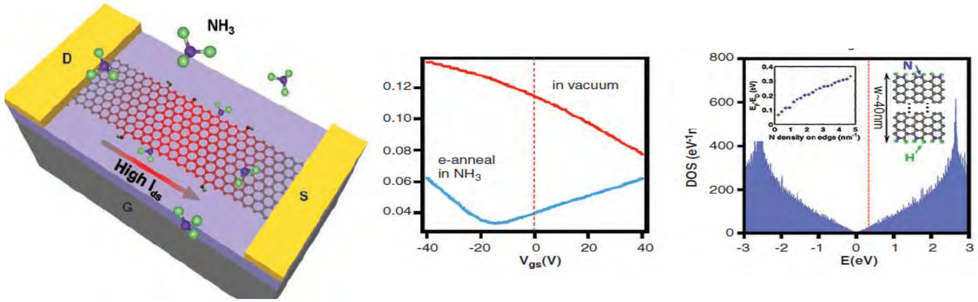
K. S. Novoselov, et al., Nature (2005)

Disadvantage of graphene

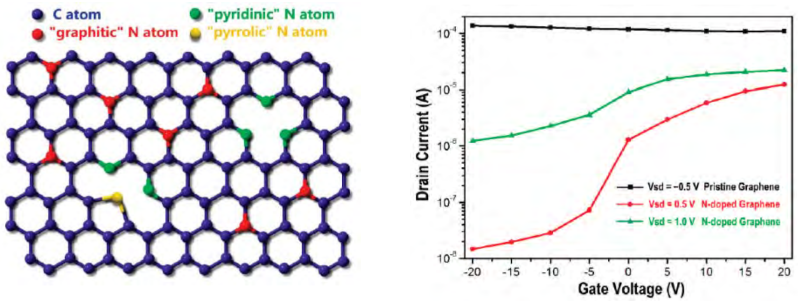
1. **Low on/ off ratio**
2. **Usually P-type in air**
3. **Poor air stability**

Doped graphene

1. Covalent functionalized or substitutional doping

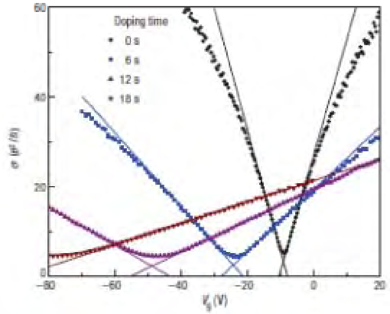


Xinran Wang, *etal.* Science (2007)

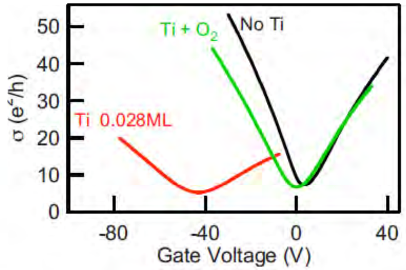


Dacheng Wei, *etal.* Nano lett. (2009)

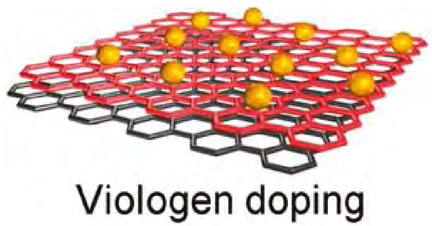
2. Surface charge transferred doping



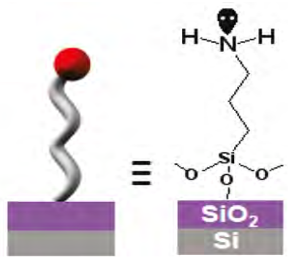
J.–H. Chen. *et al.* Nature (2008)



McCreary, K. *etal. Appl. Phys. Lett.* **2011**



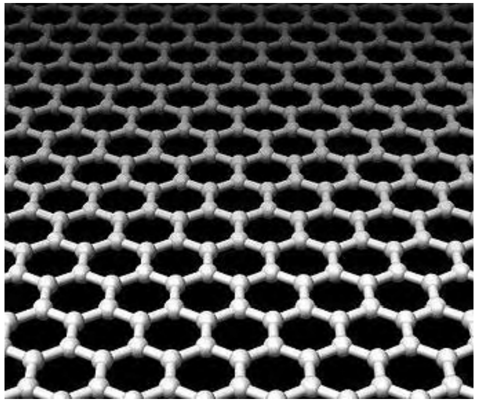
Yu, W. *etal. Nano Lett.* **2011**



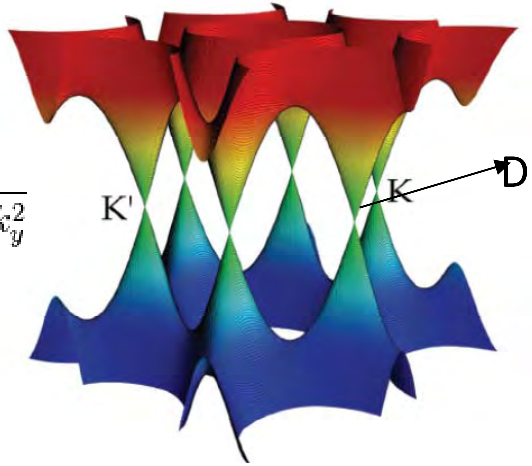
Wang, Y.; *etal. J. Phys. Chem. C* (**2008**)

- Most of doping methods could considerably damage carrier mobilities of graphene.
- The doping level could not easily be easily controlled.
- The doping devices are very vulnerable to environment, especially for n-type doping.

High transparency of Graphene

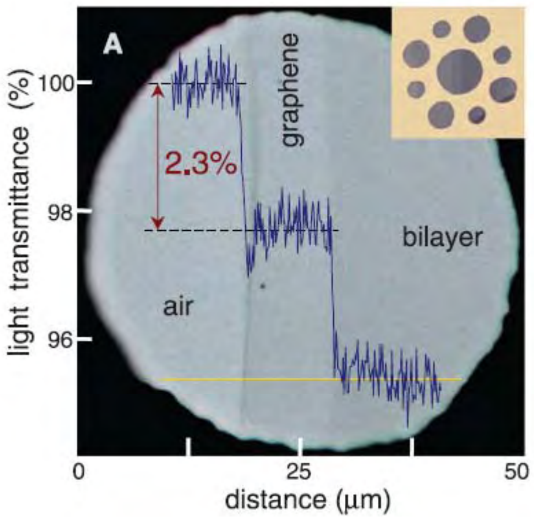


$$E = \hbar v_F \sqrt{k_x^2 + k_y^2}$$



Electronics

- **Zero effective mass near the Dirac point**
- **High carrier mobility >15,000 cm^2/ V^{-1}s^{-1}**
- **Low Resistivity about 10^{-6} Ω·cm, (< siliver)**
- **etc…**



Nair et al., Science, (2008)

Optics

1. **One atomic layer absorption** $\frac{\pi e^2}{\hbar c} = \pi\alpha = 2.3\%$
2. **High transparency**

Great potential for electronic and optoelectronic applications!

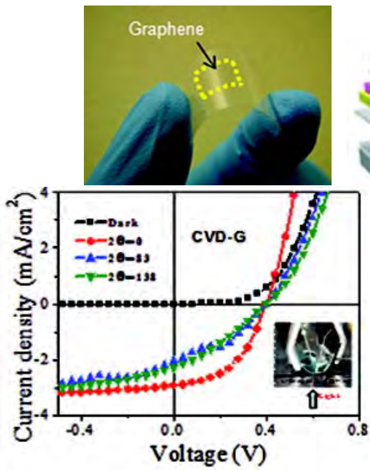
Optoelectronics application of Graphene

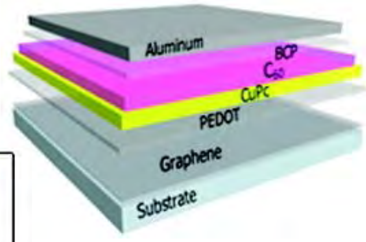
- **Transparent conducting electrode**

TOUCH PANEL

Bae, S. *et al.*
Nature Nanotech. ***4, 574–578 (2010).***

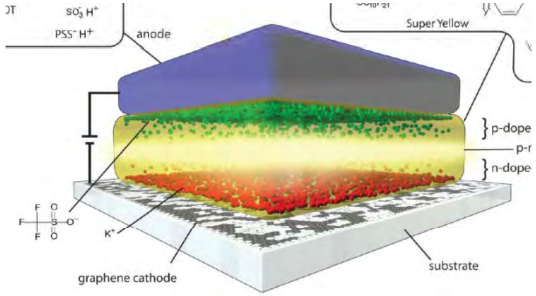
SOLAR CELL





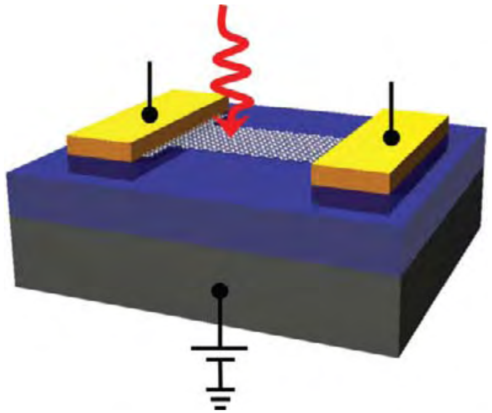
De Arco, L. G. *et al*
ACS Nano ***4,*** **2865–2873 (2010)**

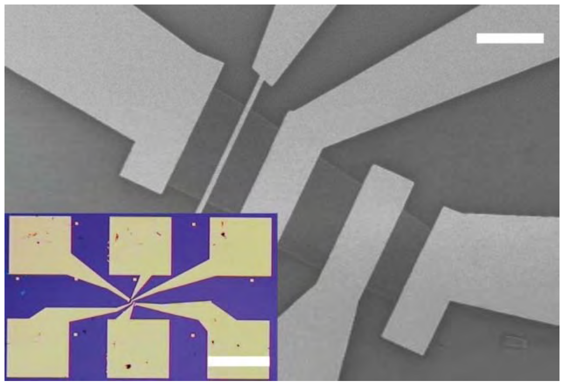
Light emitting diode

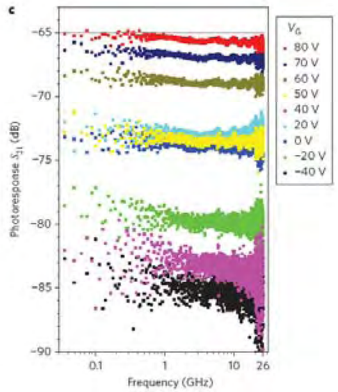


Matyba, P. *et al.*
ACS Nano ***4, 637–642 (2010).***

- **Ultra fast Photodetector**





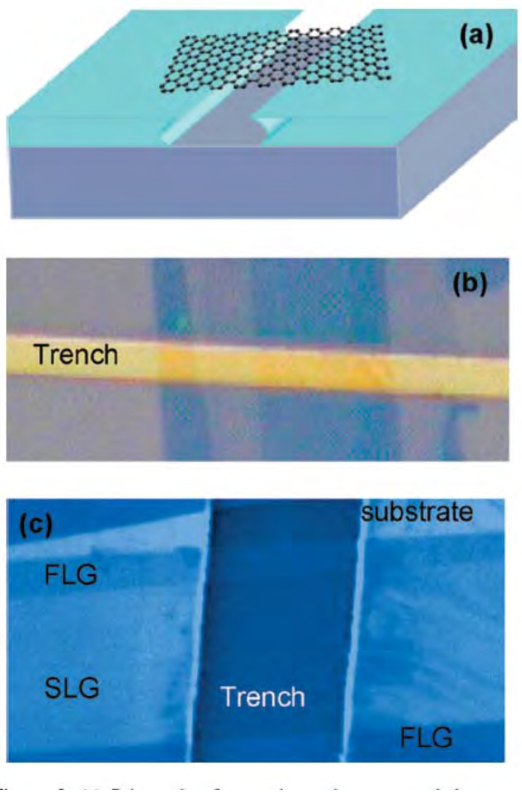


Xia, F. *et al. Nature Nanotech.* ***4, 839–843 (2009).***

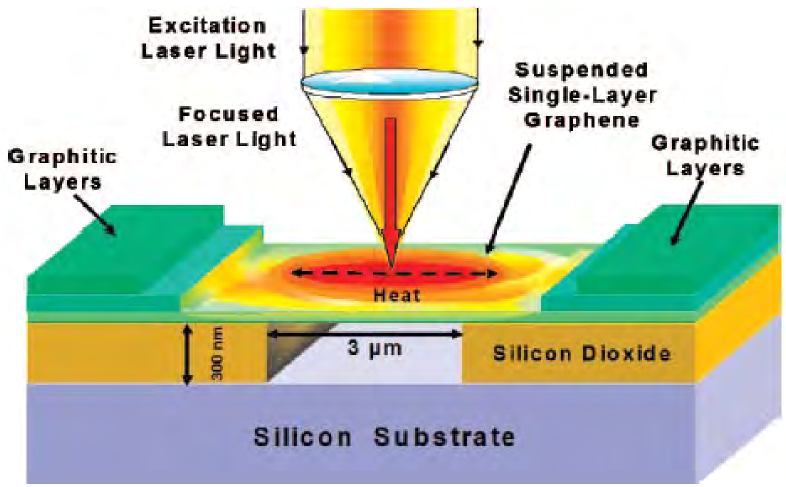
Thermal conductivity of graphene

Table 1. Room Temperature Thermal Conductivity in Graphene and CNTs

sample type	K (W/mK)	method	comments	ref
SLG	~4840–5300	optical	individual; suspended	this work
MW-CNT	>3000	electrical	individual; suspended	Kim et al.[15]
SW-CNT	~3500	electrical	individual; suspended	Pop et al.[16]
SW-CNT	1750–5800	thermocouples	bundles	Hone et al.[17]

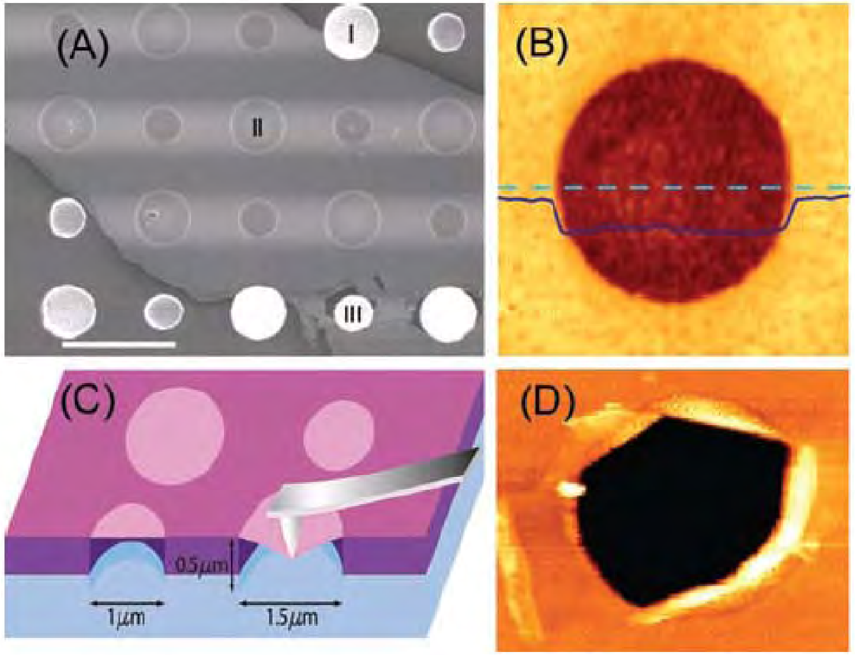


The extremely high value of the thermal conductivity suggests that graphene can outperform carbon nanotubes in heat conduction.



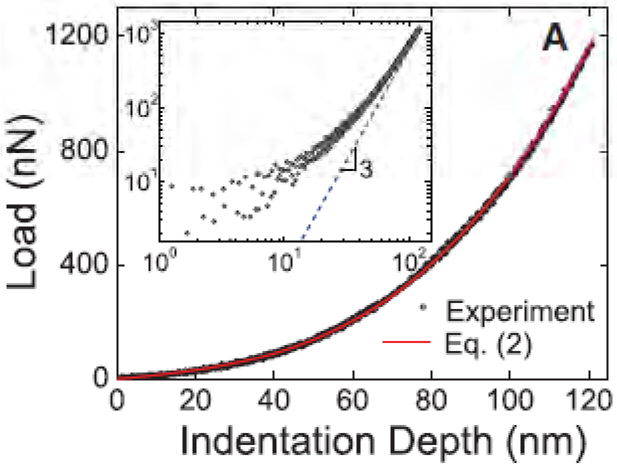
Nano Letters, 2008,Vol.8, 902

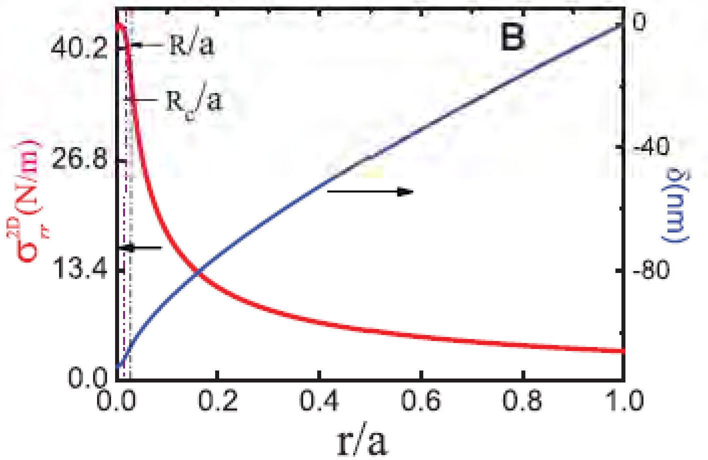
Mechanical properties of graphene



1. These experiments establish graphene as the strongest material ever measured.

2. The results show that atomically perfect nanoscale materials can be mechanically tested to deformations well beyond the linear regime.





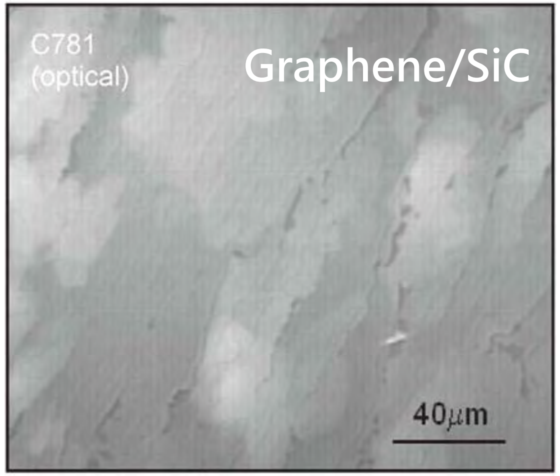
Hones et al, Science,Vol. 321, p385, 2008

Synthesis of Graphene

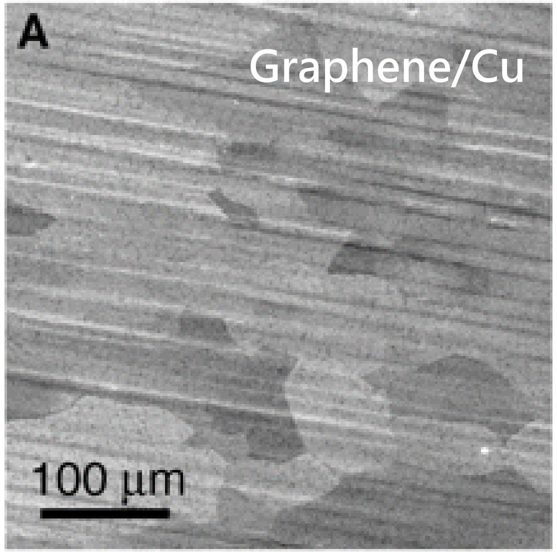
- **Mechanical exfoliation**
- **Epitaxial growth on silicon carbide**
- **Epitaxial growth on metal substrates**
- **Reduction of graphene oxide**

  => solution processible, mass producible, simple and cheap

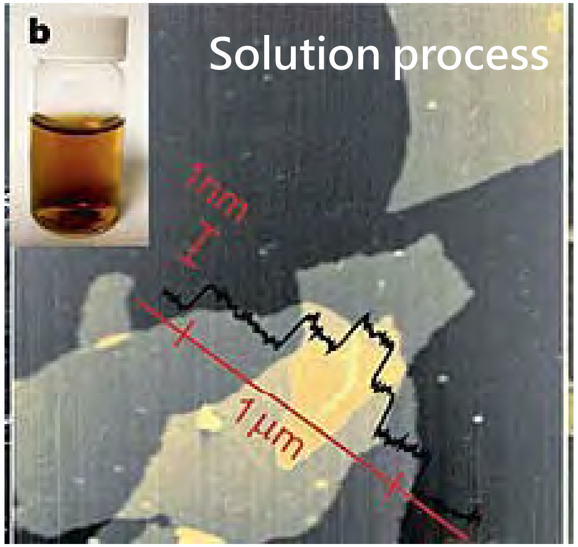
Novoselov et al., *Science* (2004)



de Heer et al, *Science* (2006)



Ruoff et al., *Science*, vol. 324, pp1312-1314, **2009**



Sasha Stankovich, et al., *Nature* 442, 282-286, **2006**

Exfoliation process

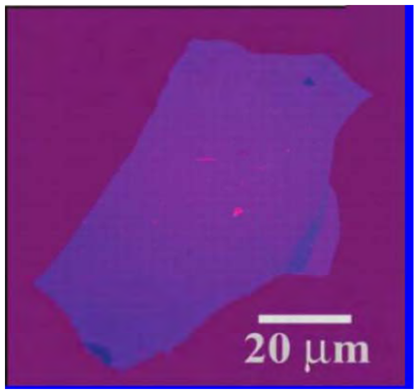
– In 2004, Andre Geim and Konstantin Novoselov suggest this method[4]

– Use tapes to split one layer of C atoms from graphite and form graphene flake

– Free-standing graphene

– Demonstrate the first graphene transistor

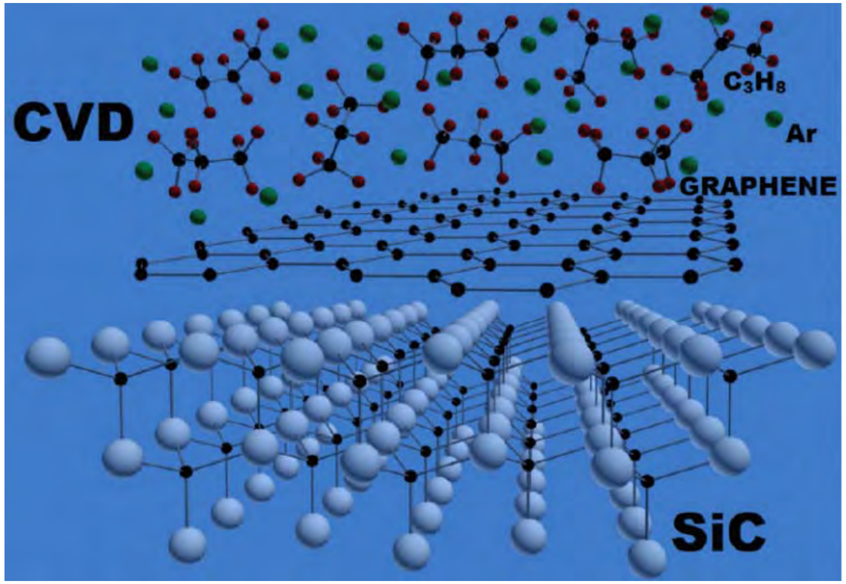
– 2010 Nobel Prize in Physics



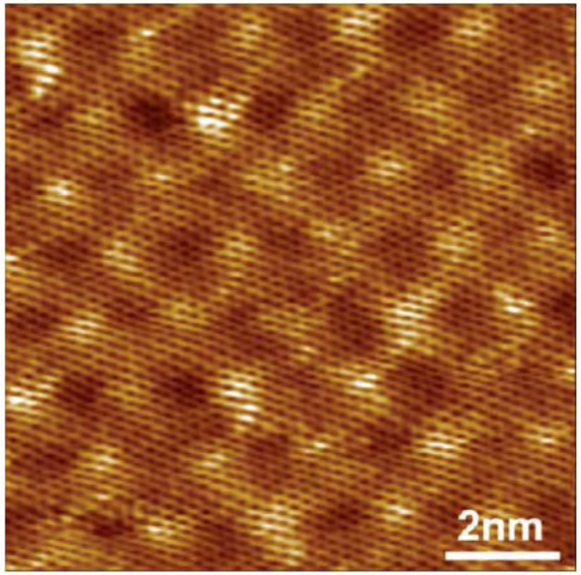
Novoselov, K. S.; Geim, A. K. et al, *Science* **306** (5696), 666 (2004)

How to find the atomic layer “graphene” from repeatedly split graphite crystals by adhesive tape

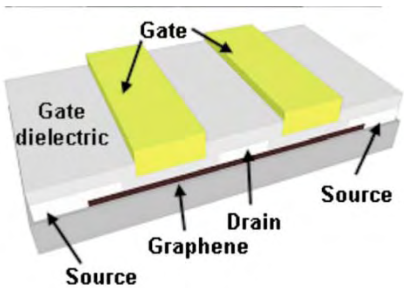
Epitaxial Graphene on SiC substrate by Chemical Vapor Deposition



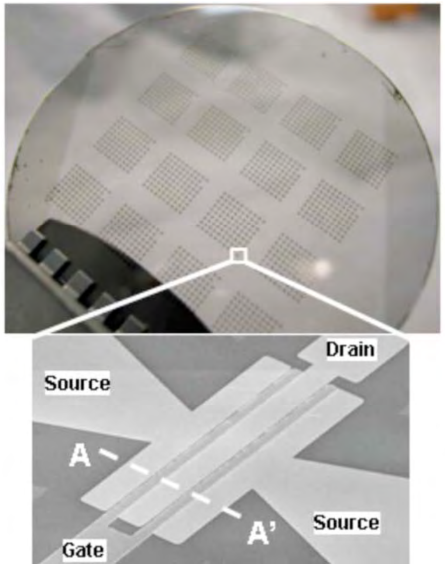
STM image of a CVD-EG layer grown on a 4HSiC(0001) substrate



Strupinski, W. et. al., Nano Lett. 2011, 11, 1786–1791



(c)



(a)

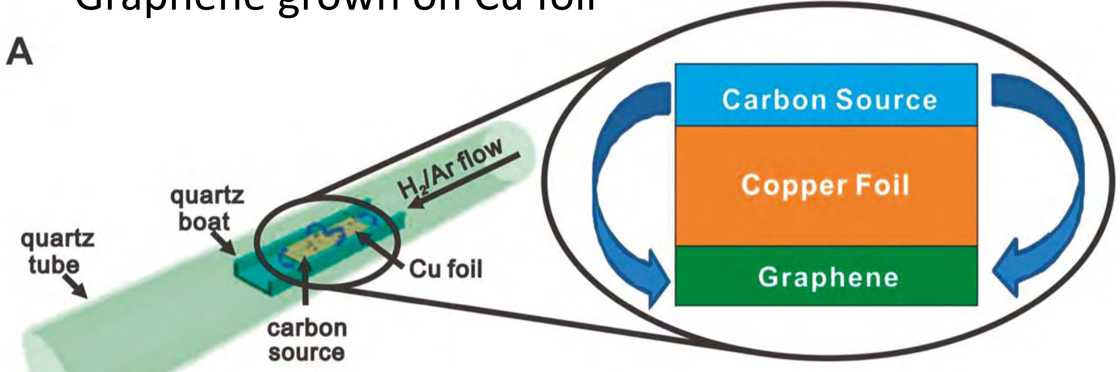
(b)

IBM wafer-scale epitaxial graphene

J. Vac. Sci., B. 28, 985,2010

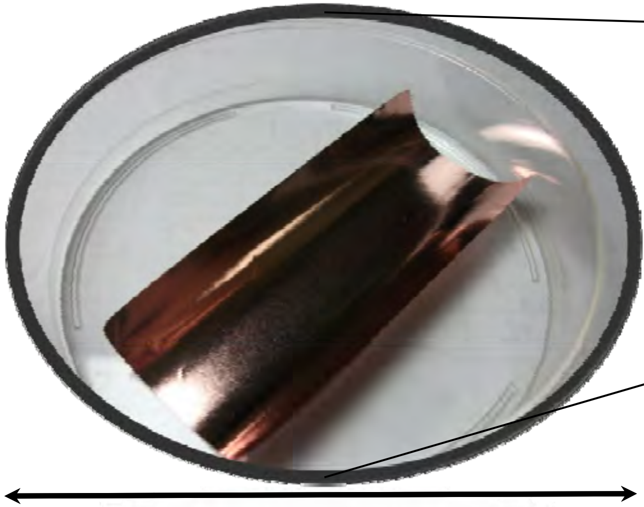
Large area fabrication of graphene on Cu by using CVD processes

Graphene grown on Cu foil



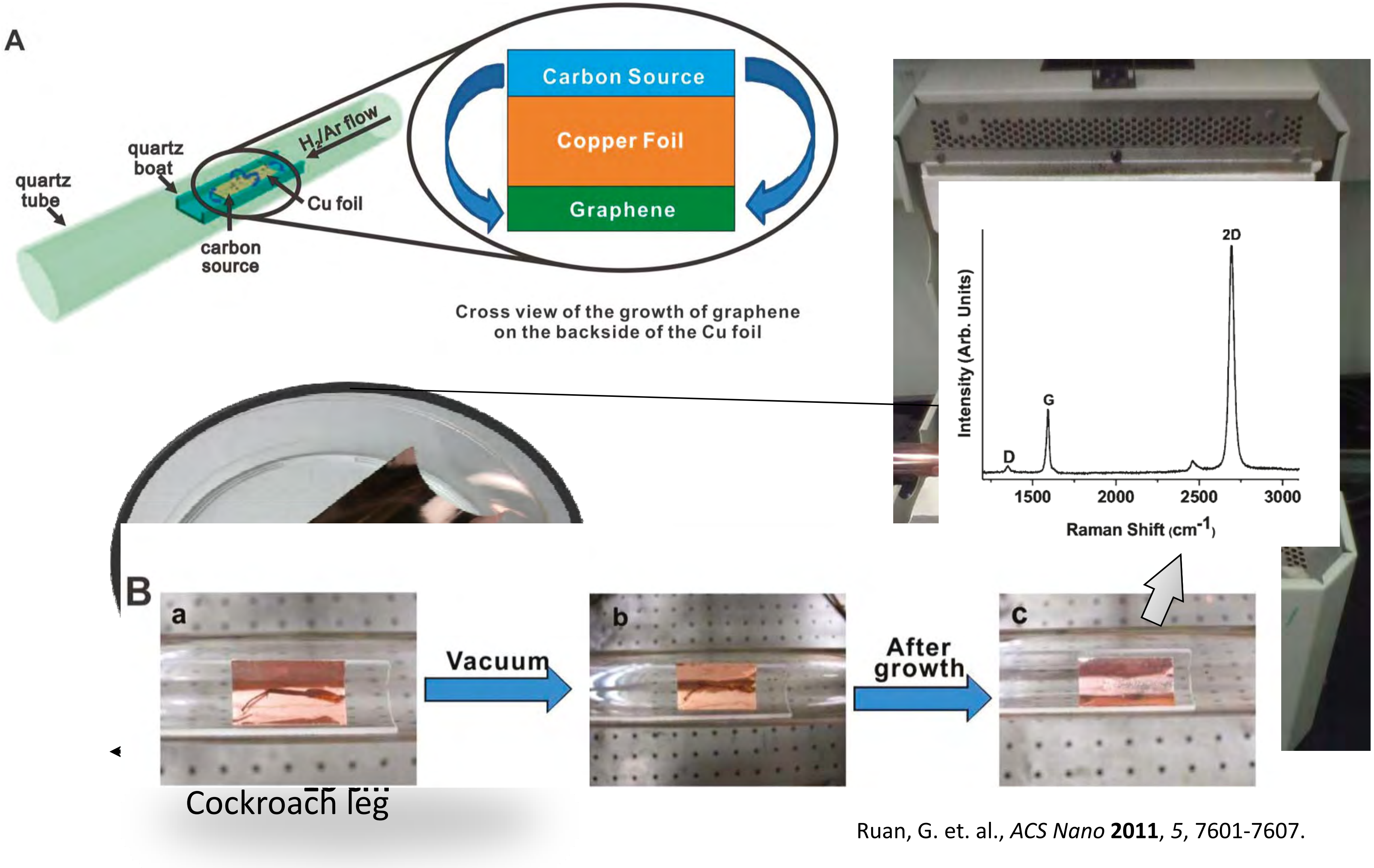
Cross view of the growth of graphene on the backside of the Cu foil

Ruan, G. et. al., *ACS Nano* **2011**, *5*, 7601-7607.



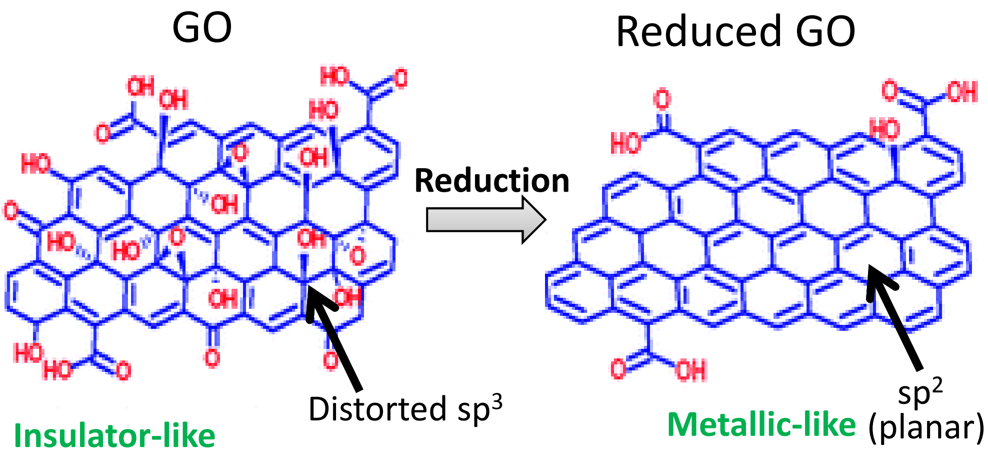
Ruoff et al., *Science*, vol. 324, pp1312-1314, **2009**

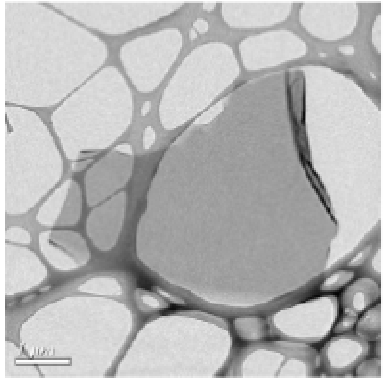
Fabrication process of CVD graphene

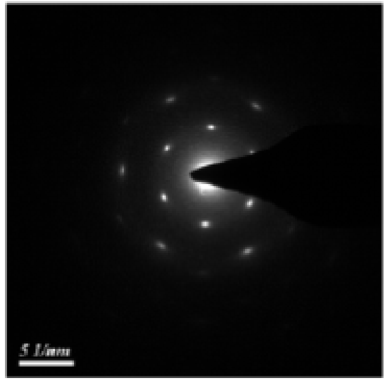


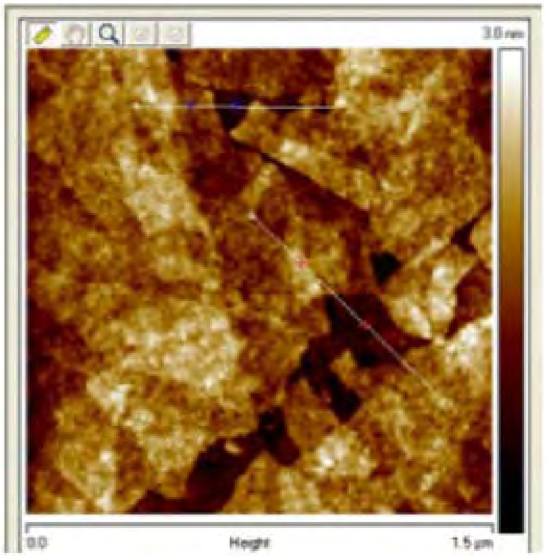
Ruan, G. et. al., *ACS Nano* **2011**, *5*, 7601-7607.

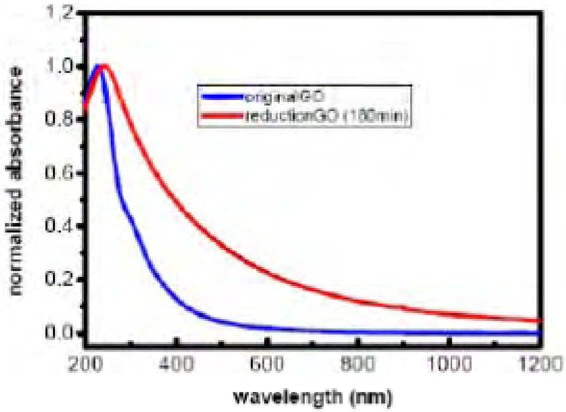
Chemical exfoliation of graphene from reduced graphene oxide







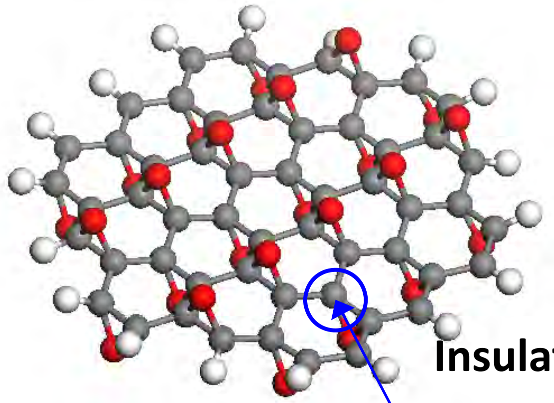




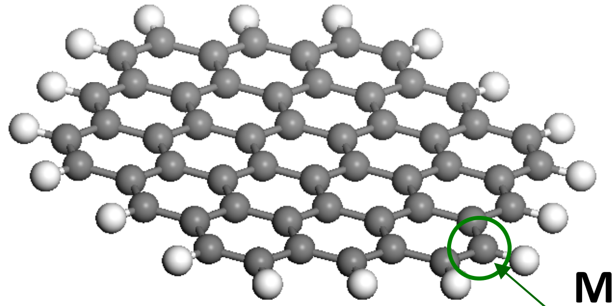
Eda *et al*. *Nature Nanotech.* 3 270-274 (2008)

Atomic and electronic structure of GO/Graphene

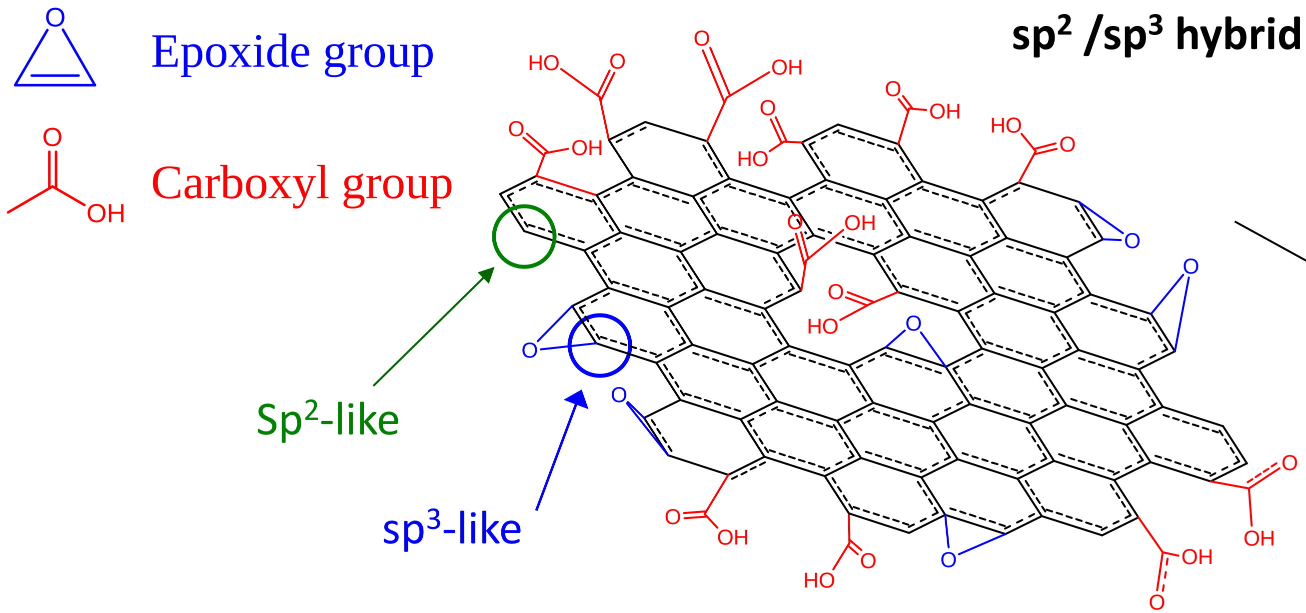
Ideal structure

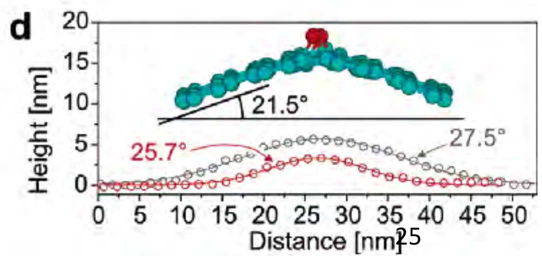


Reduction



sp2 /sp3 hybrid (Real structure)





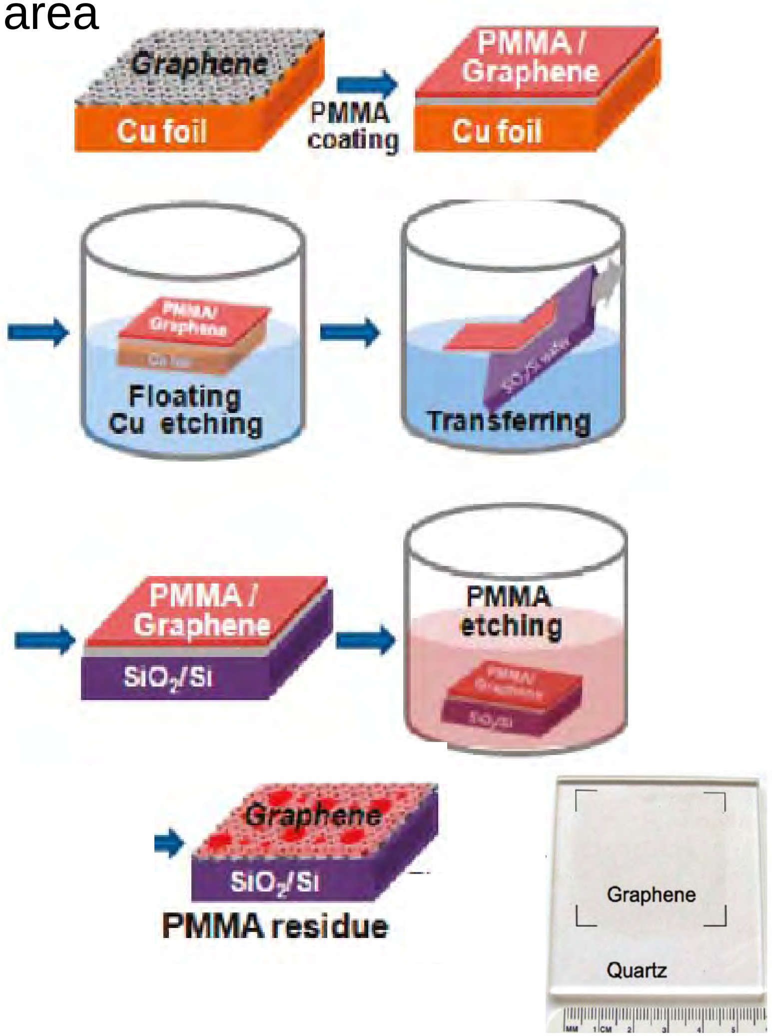
Akasay et al, J of Phys. Chem. B Lett., 110, 8535, 2006

Transfer of graphene

Two Traditional Transfer Methods for CVD Graphene in the World

PMMA Transfer Method

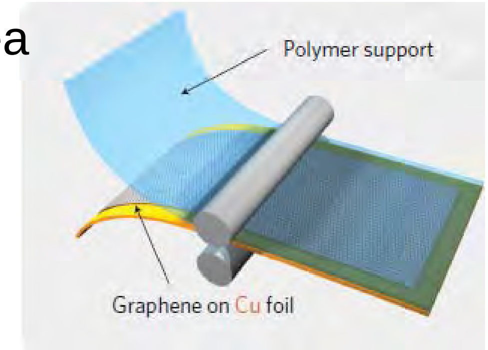
Small area

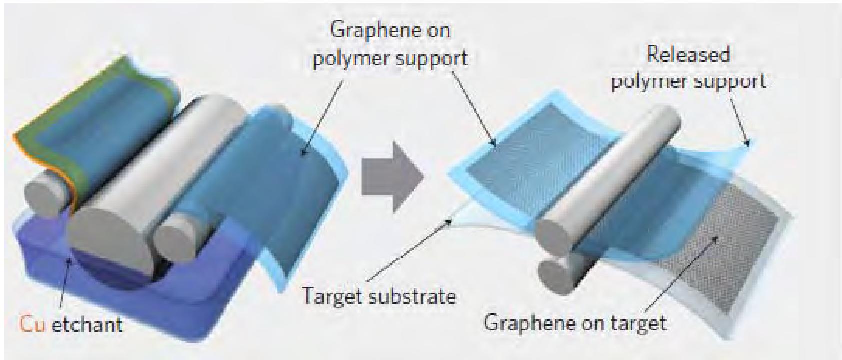


Lee, W. H., et. al, *J. Am. Chem. Soc.* , **2010**, 133 , *4447*

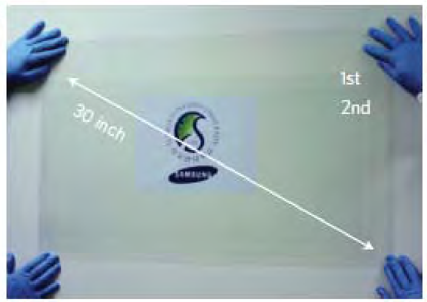
Roll to Roll Transfer Method

Large area



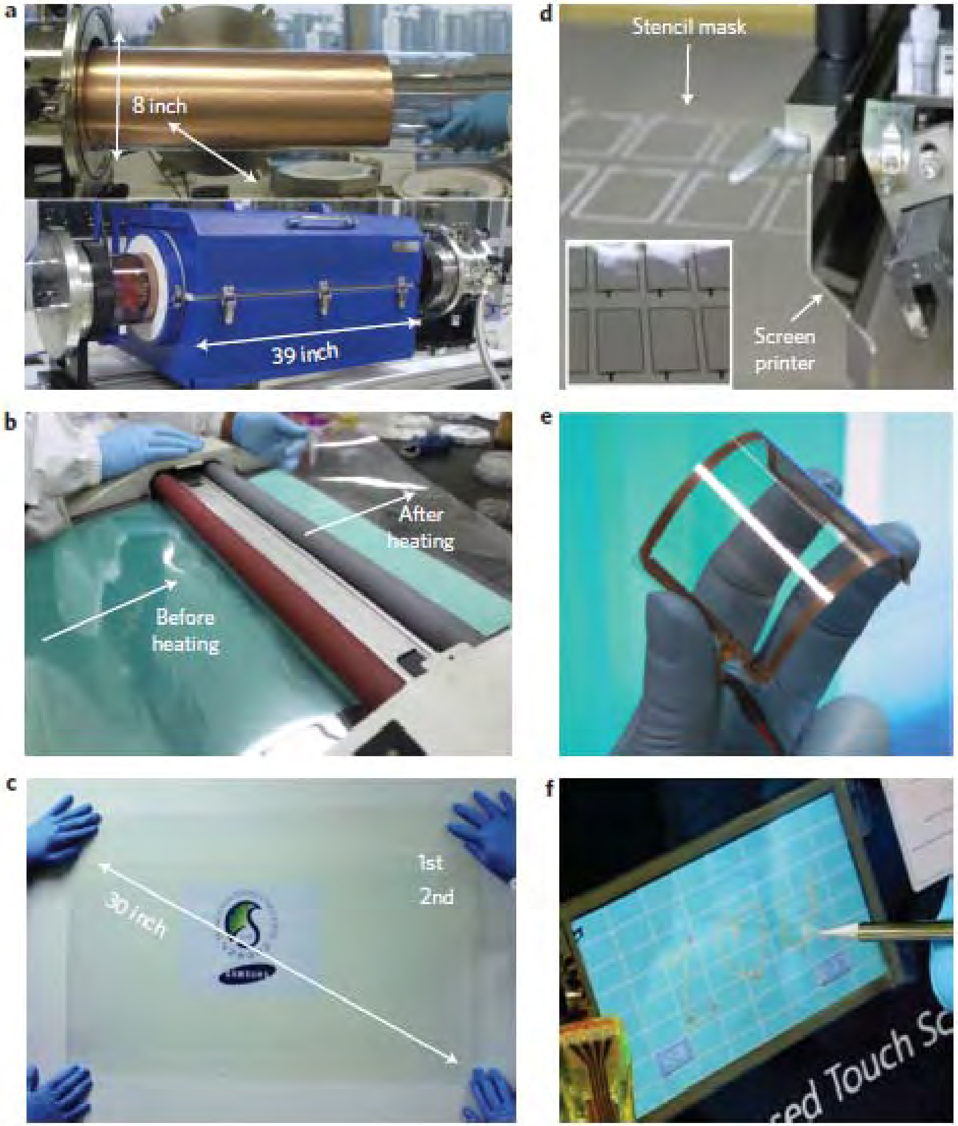


c



Bae, S., et. al., *Nat. Nanotech.*, **2010**, *5*, 574

Roll-to-roll production of 30-inch graphene films for transparent electrodes



Bae, S., et. al., *Nat. Nanotech.*, **2010**, *5*, 574

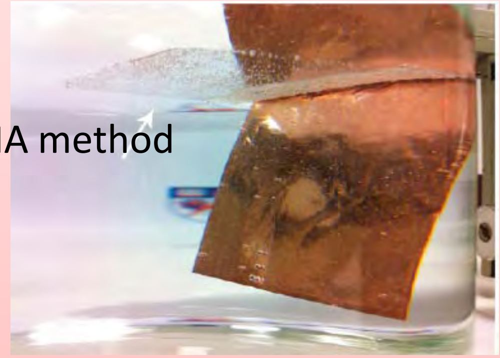
Processes of large-area CVD graphene film transferred onto arbitrary substrate

Graphene Growth

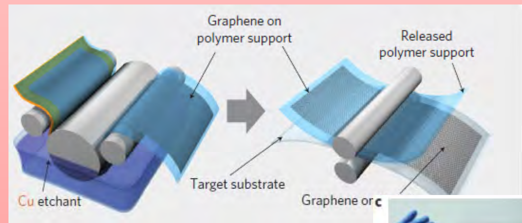
Graphene on Cu foil

Graphene Transfer

PMMA method



Organic support protection

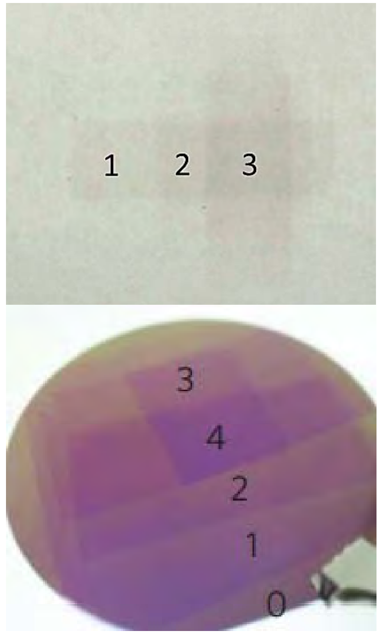


R2R method

A critical step

Cu foil Etching

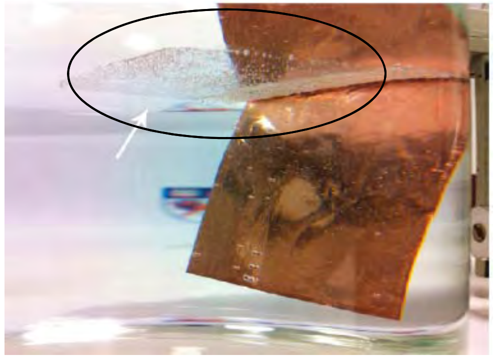
Graphene Film



Yu Wang *et al*, *ACS Nano*, **2011**, 5 , 9927–9937
Bae, S., et. al., *Nat. Nanotech.*, **2010**, *5*, 574

Problems of PMMA and R2R Transfer Methods

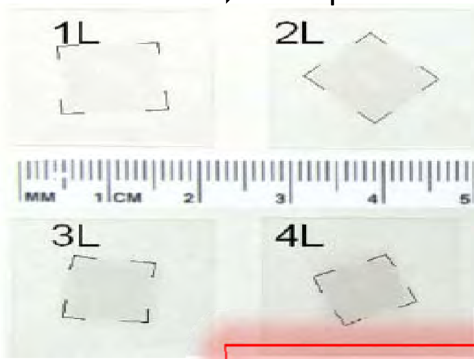
PMMA method

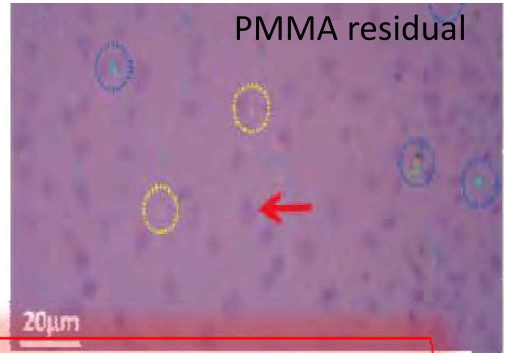


PMMA protection

Difficulty in handling

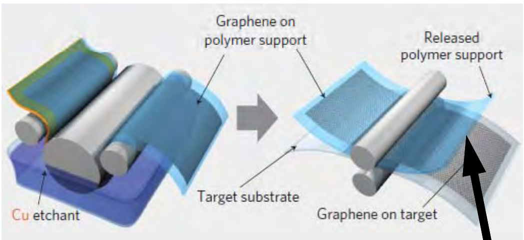
→ stack problem





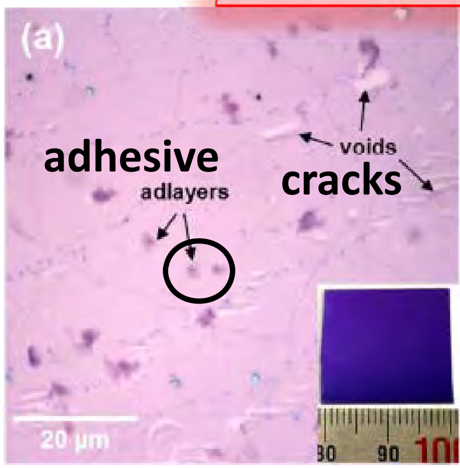
Organic Residue

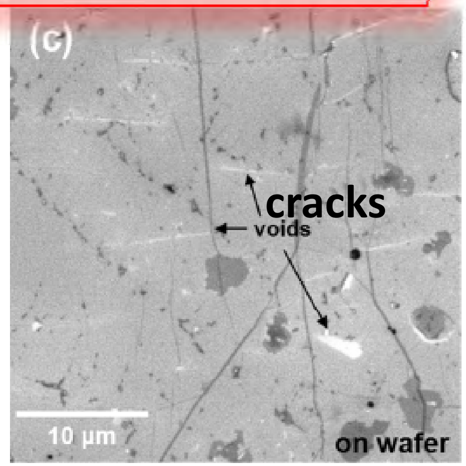
R2R method



Thermal released tape

1. undesired mechanical defects
2. organic adhesive from tape





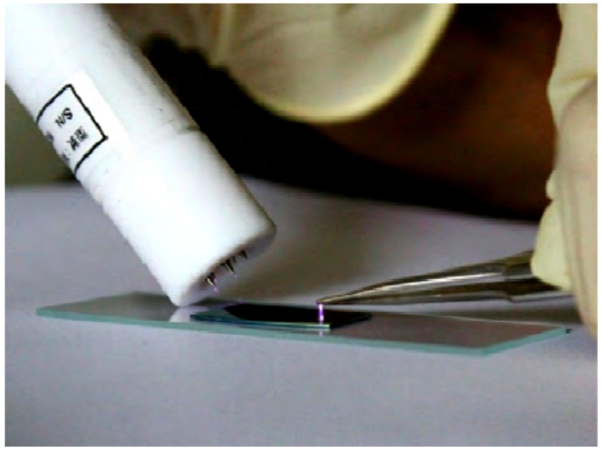
Junmo Kang ***et al***, *ACS Nano*, **2012,** 6, 5360.

Xuesong Li ***et al***, *Nano Lett.*, **2009** , 9 , *4359–4363*

Can we transfer graphene with no organic residue ???

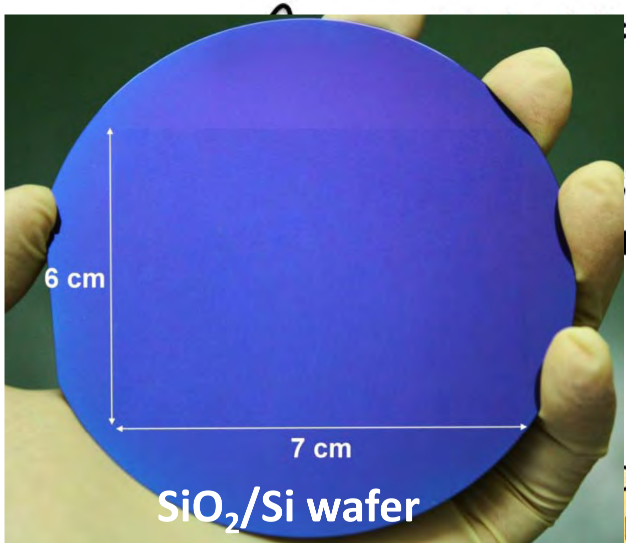
Using electrostatic attraction

Electrostatic generator

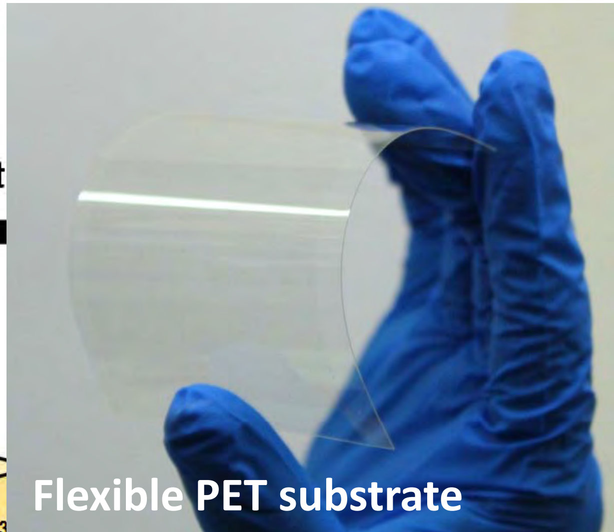


Adv. Mater. 25, 4521, (2013)
Adv. Mater. 25, 4521, (2013)

Clean-Lifting Transfer (CLT) Technique

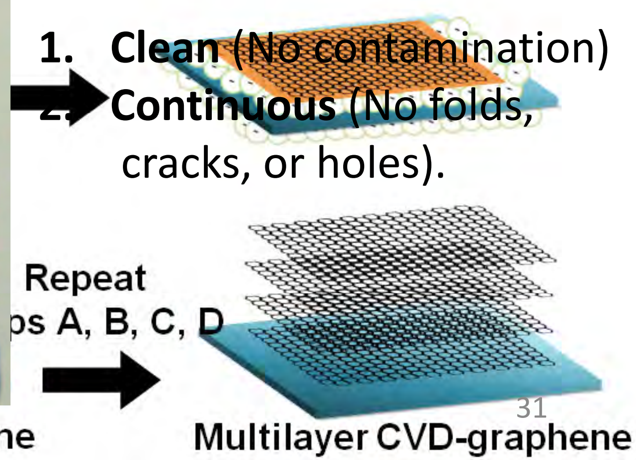


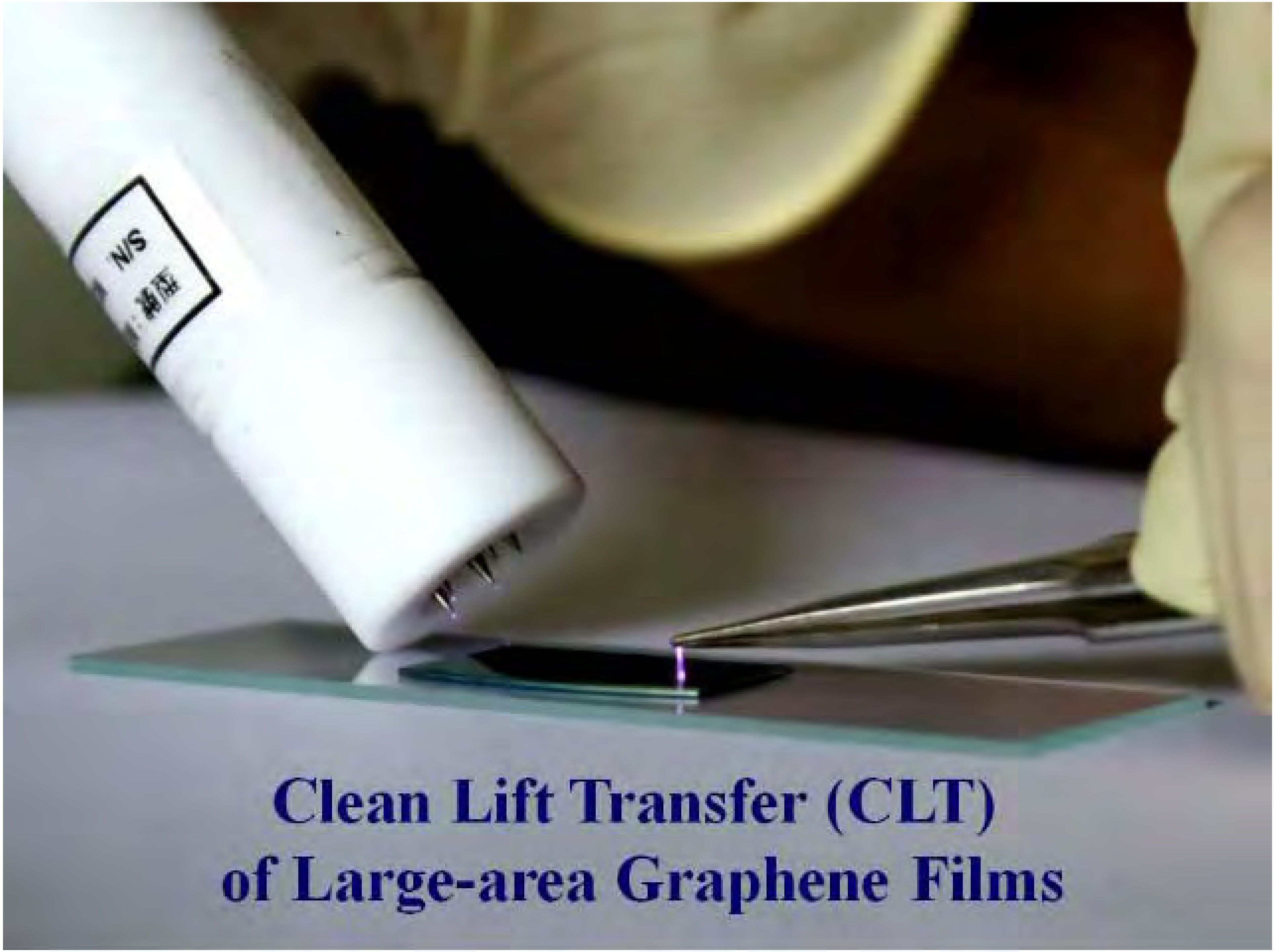
SiO$_2$/Si wafer



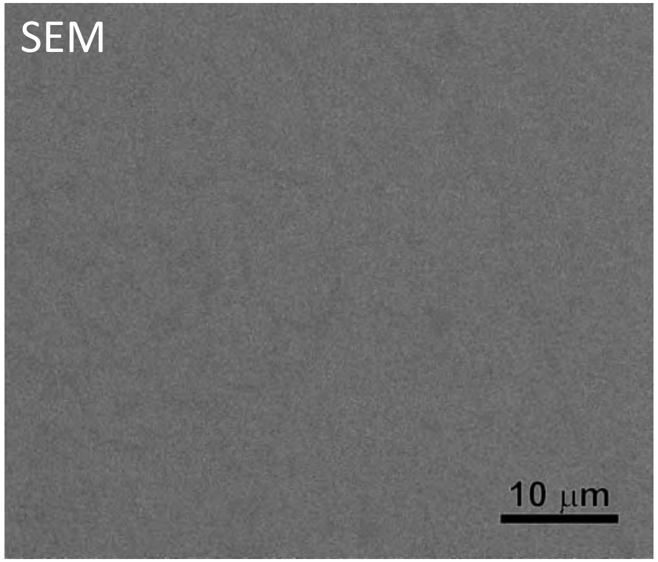
Flexible PET substrate

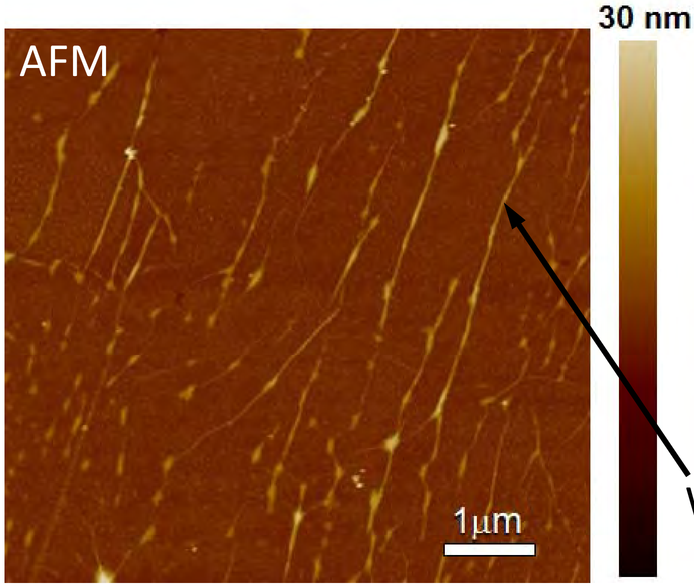
1. **Clean** (No contamination)
2. **Continuous** (No folds, cracks, or holes).




N/S
Clean Lift Transfer (CLT)
of Large-area Graphene Films

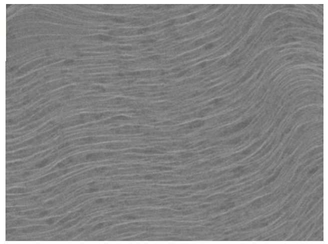
High quality CVD graphene of transferred by the CLT technique

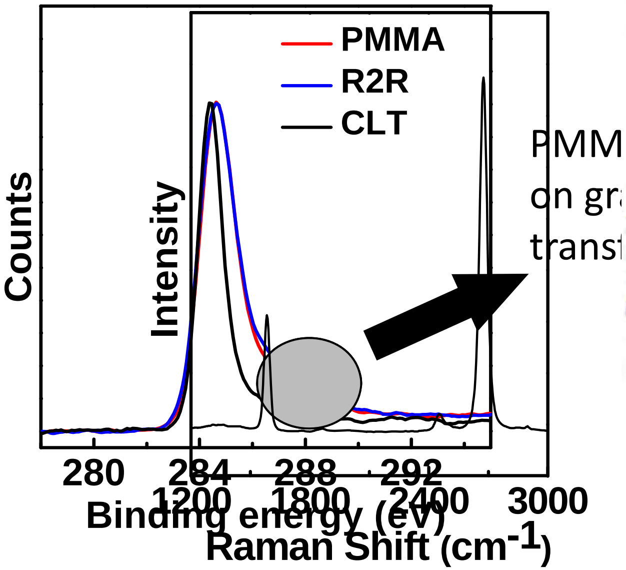




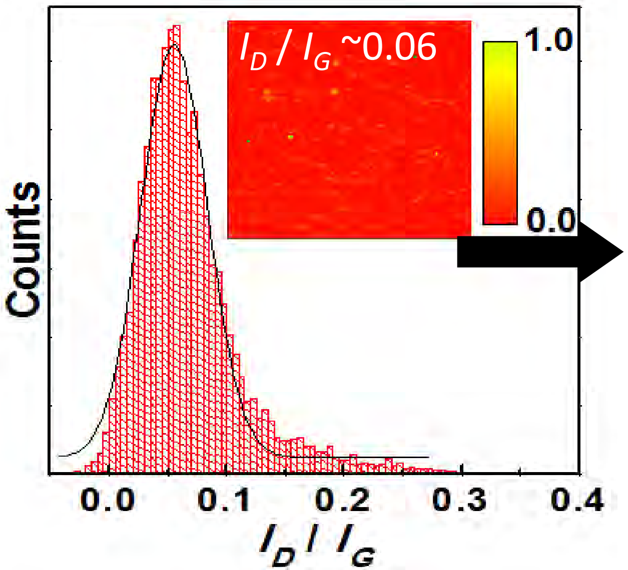
1. Clean
2. Uniform morphology
3. No significant macroscopic defects,

Wrinkles from the Cu foil



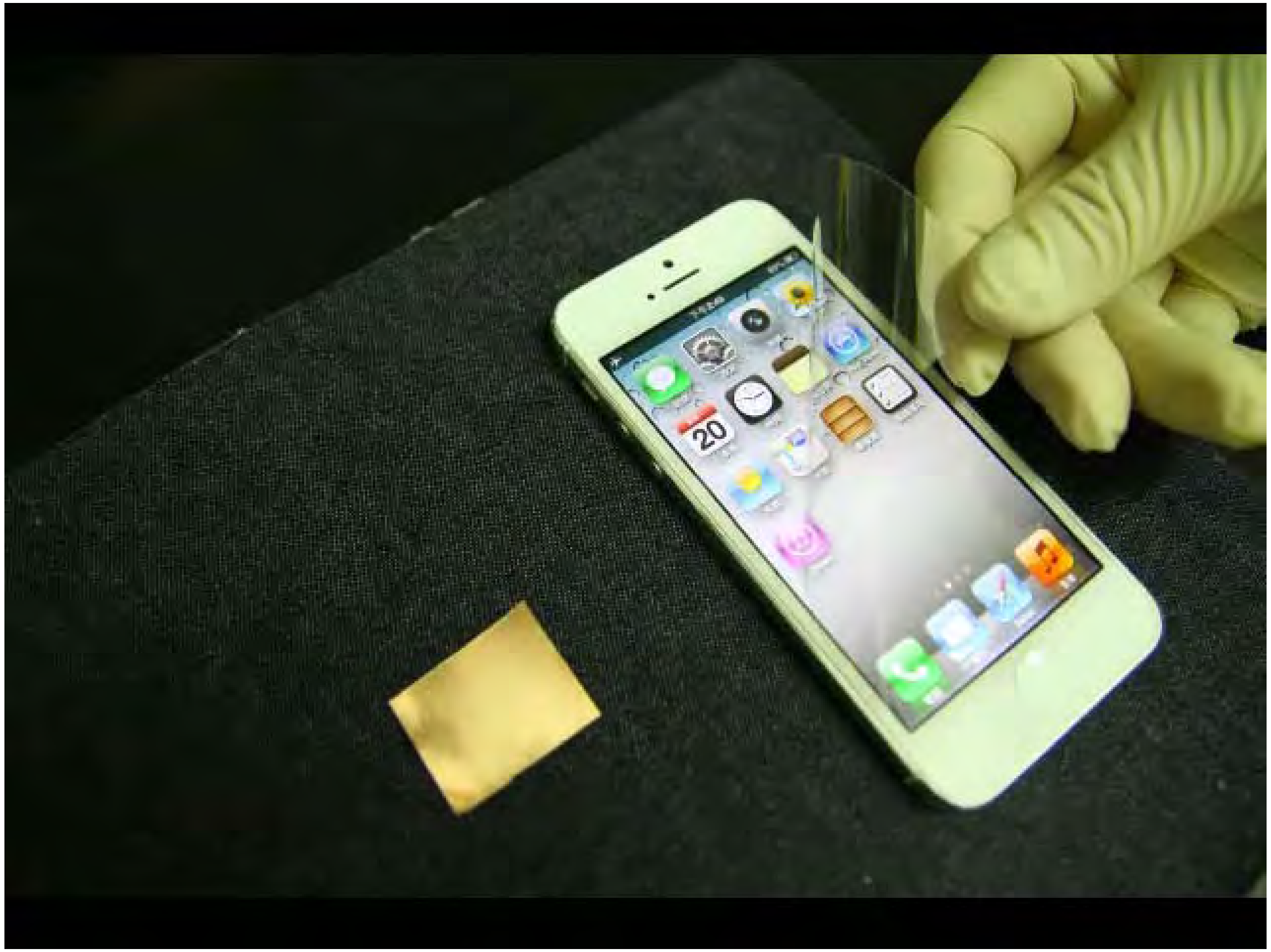


Raman mapping



1. High quality
2. Good uniformity

CLT of graphene by a screen protector

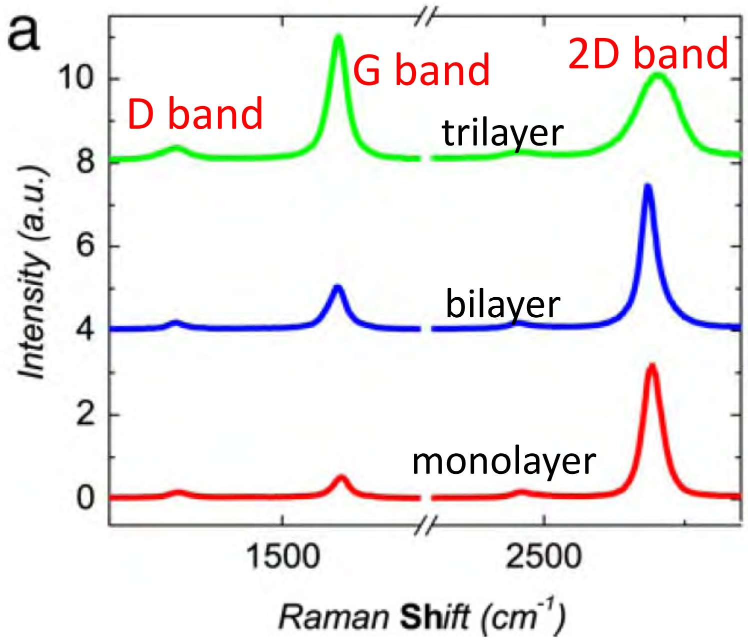


Characterizations of garphene

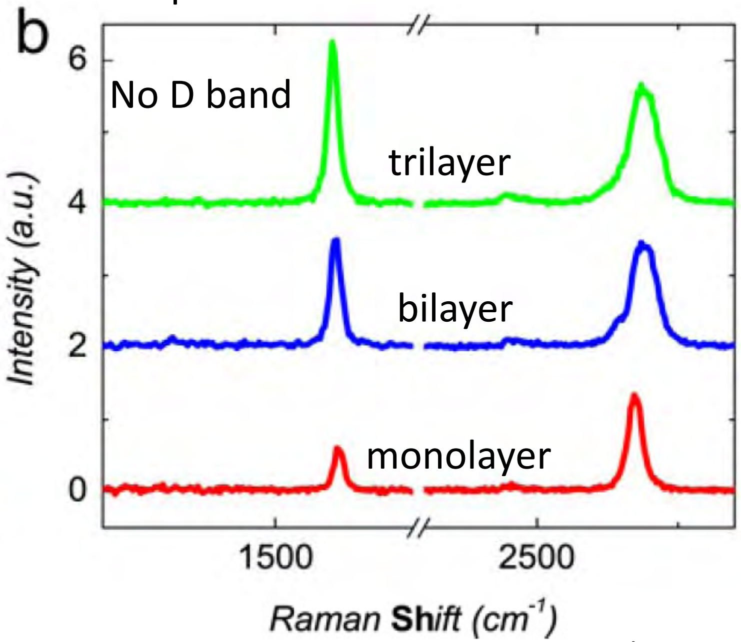
Raman Spectra of graphene

<u>**Identification of the layer number of graphene**</u>

CVD graphene grown on Ni



Graphene fron mechanical exfoliation of HOPG

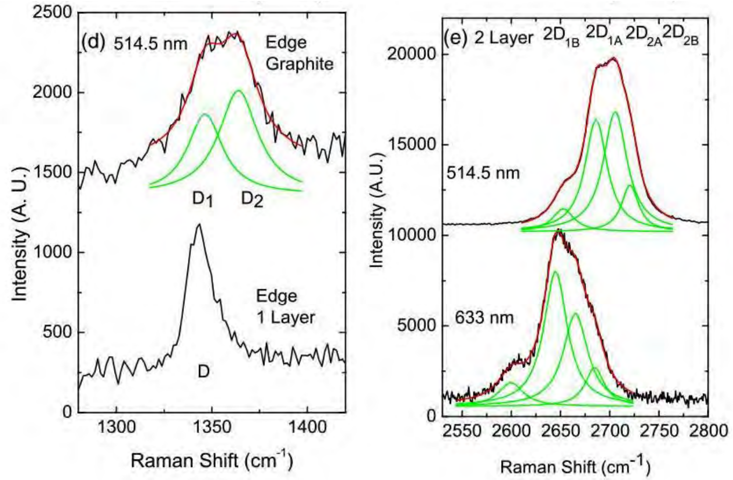


I_G / I_{2D} ~1.25

I_G / I_{2D} ~1.05

I_G / I_{2D} ~0.4

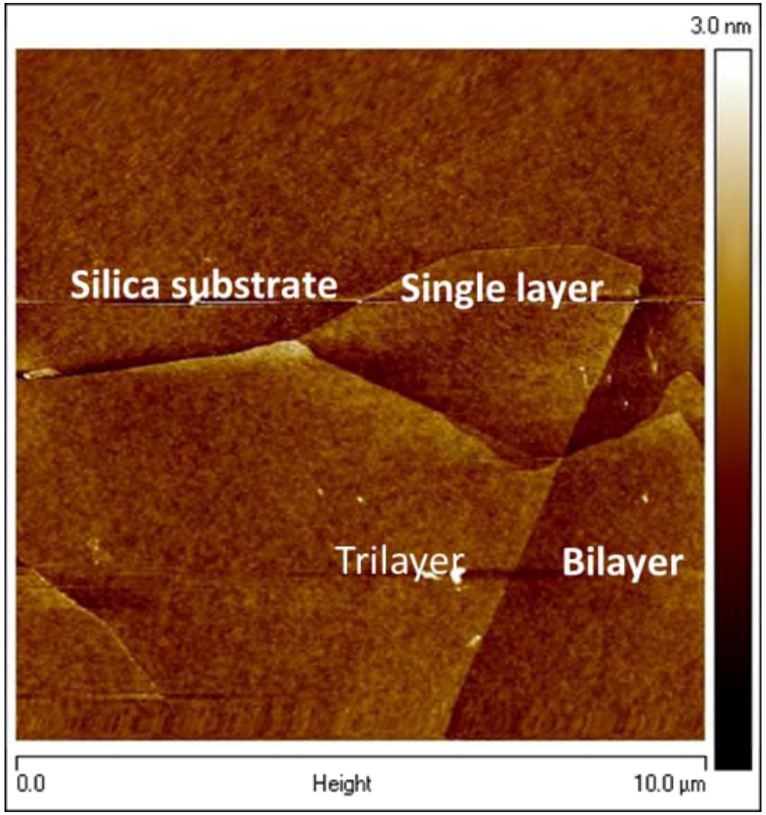
A. Reina et. al., Nano Lett. 9 (2009) 3035.



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

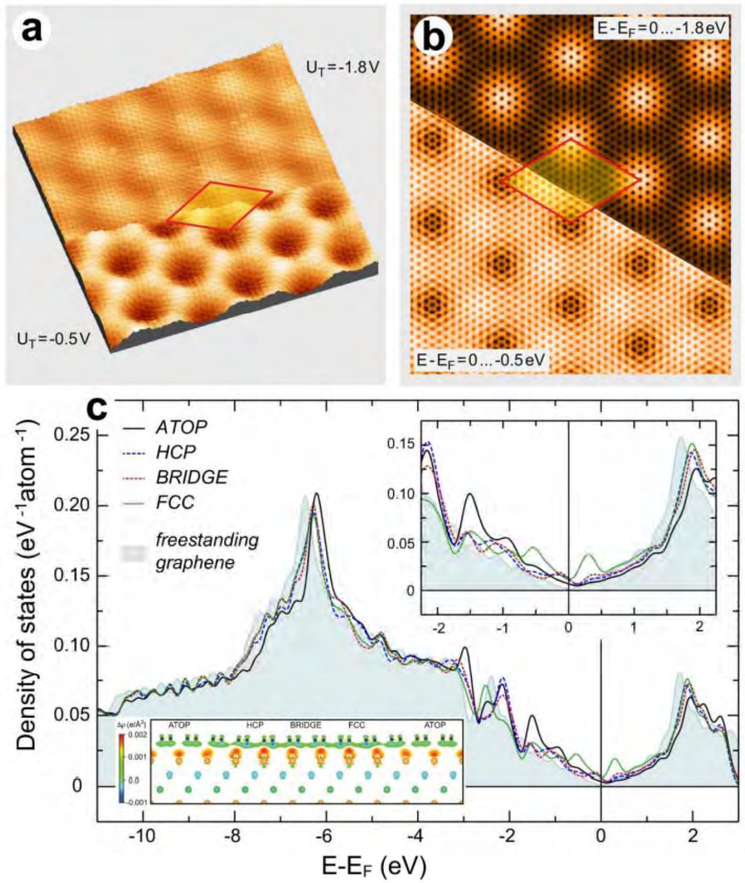
AFM and STM image of graphene

AFM images of graphene on SiO_2



STM images of graphene/Ir(111)

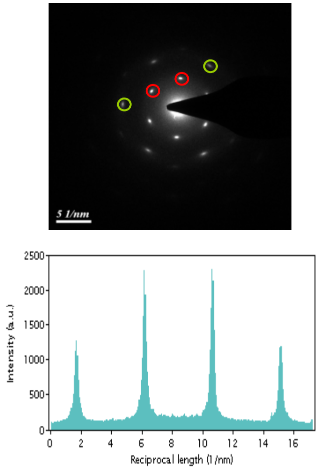
Experimental calculated



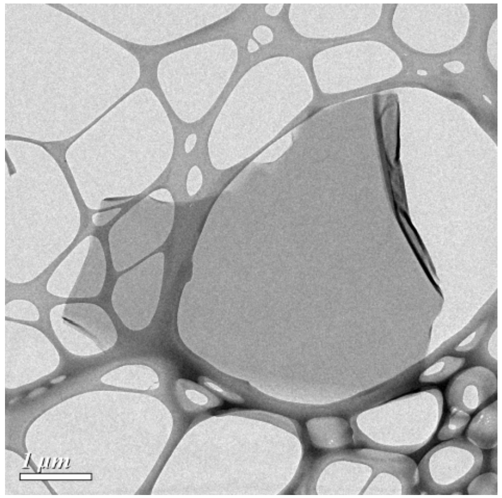
Voloshina, E. N. Science Report, 2013, 3, 1

Photothermal reduction method for GO and r-GO

(a)

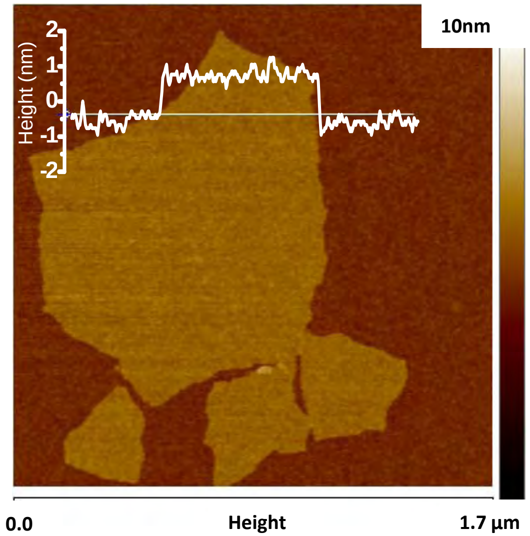


TEM of GO



(b)

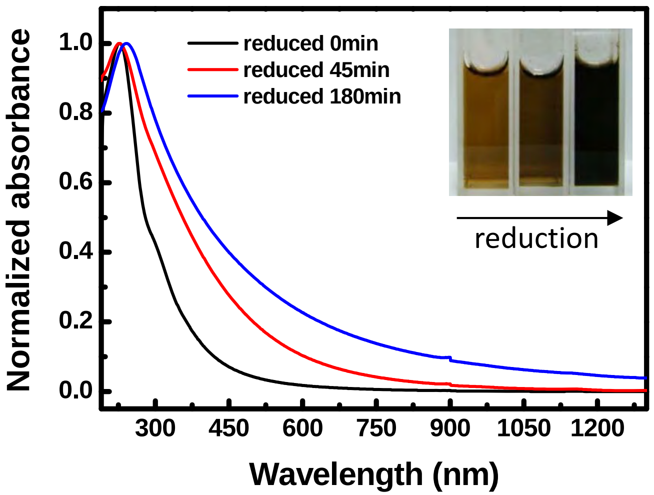
AFM of GO



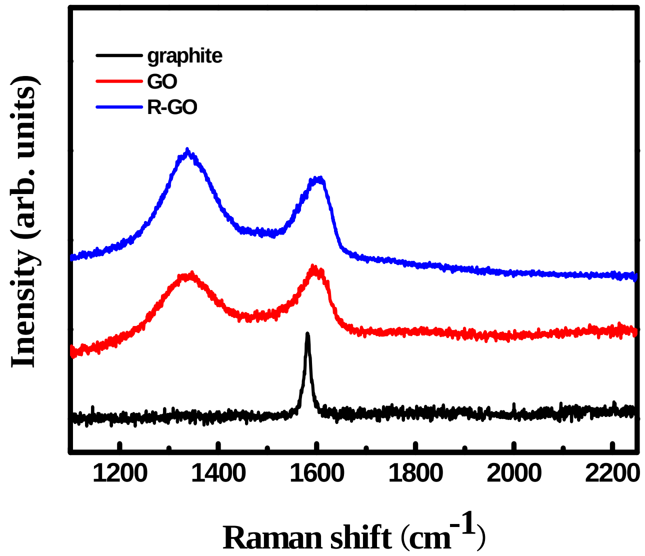
(c)

(d)

Xe Lamp



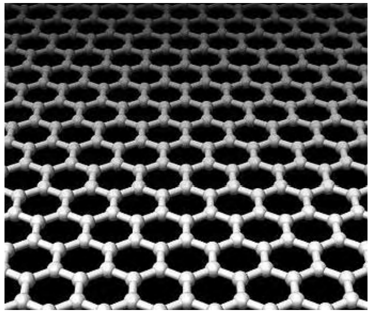
Mild reduction processes



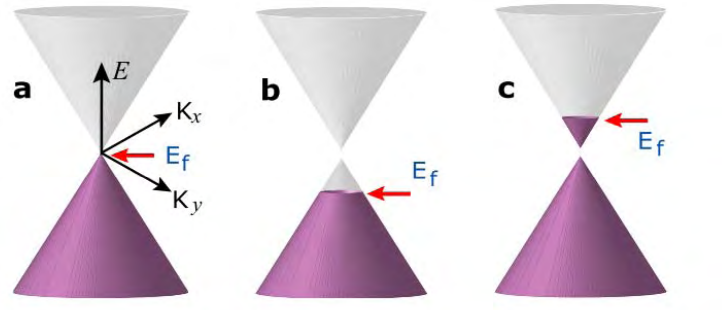
Electrical properties of graphene

Tunable electrical and optical platform of graphene

Atomically thin structure

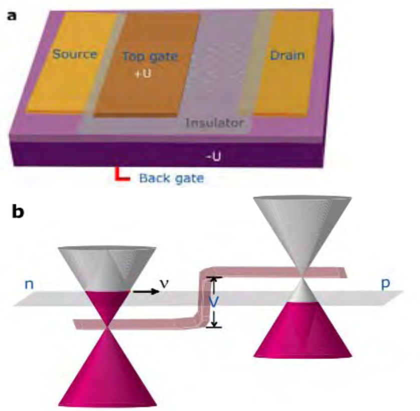


Tunable electronic structure



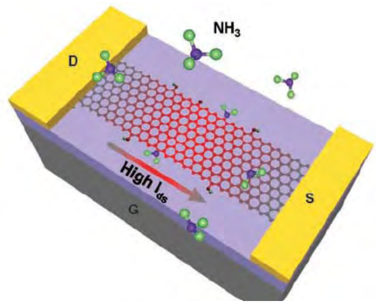
Easily modulated by electrical, or chemical , optical and mechanical methods

Electrical gating



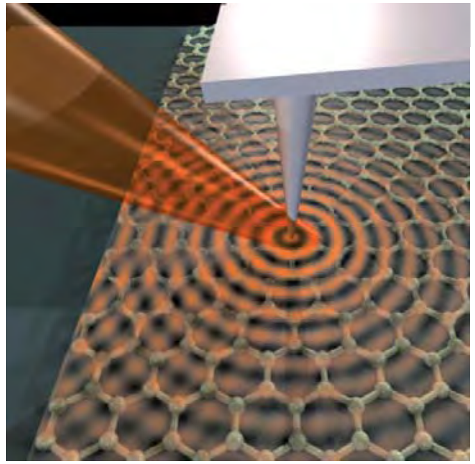
B. Guo et al., *Insciences J.* **1** (2), 80 (2011)

Chemical Doping



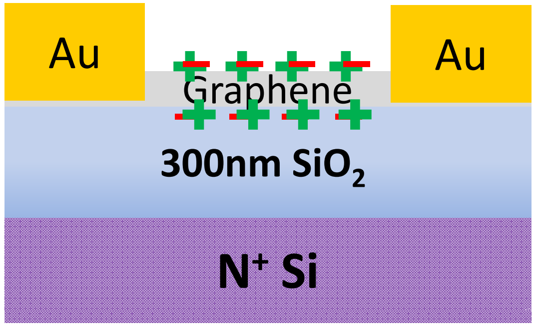
Xinran Wang, *et al.* Science (2007)

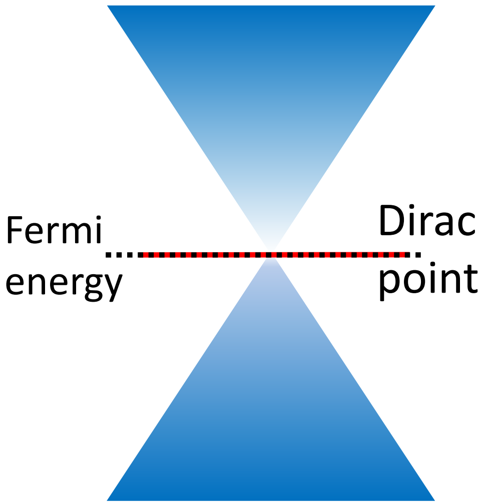
IR Nano imaging



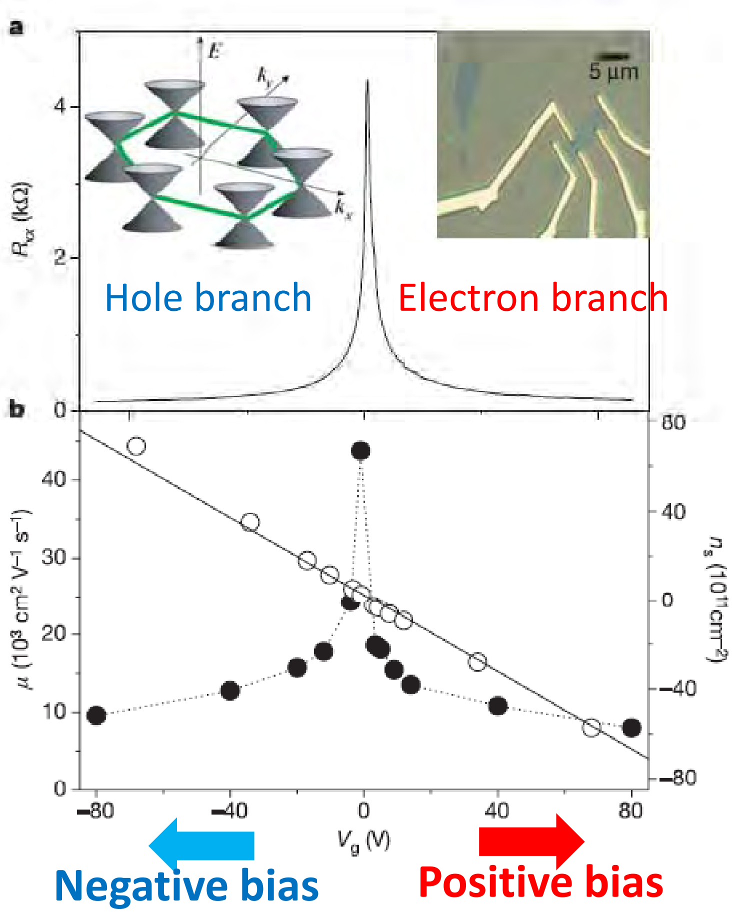
Fei. Etal, Nature, 82, V 487, 2012

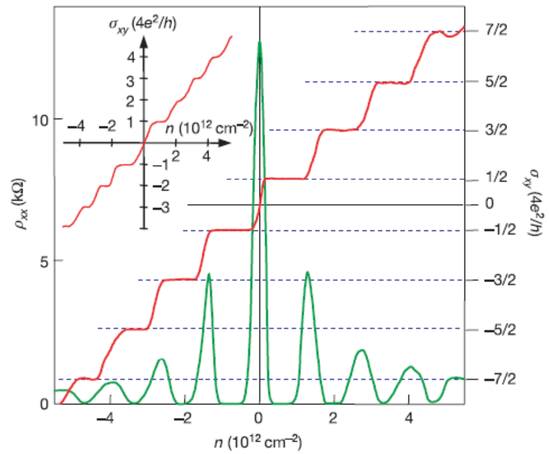
Graphene
Ambipolar transport property





Yuanbo Zhang, et al., Nature(2005)

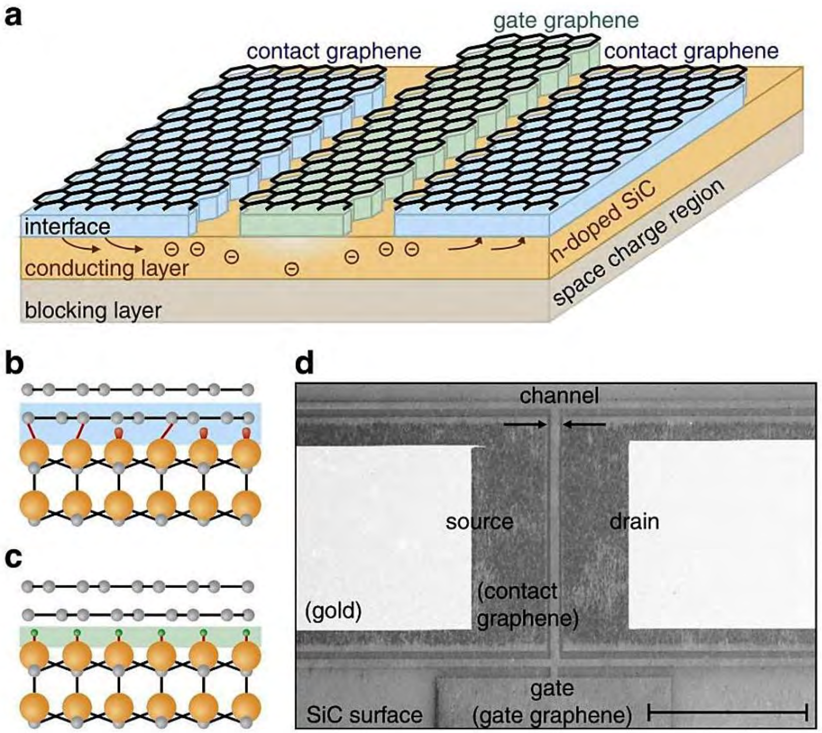




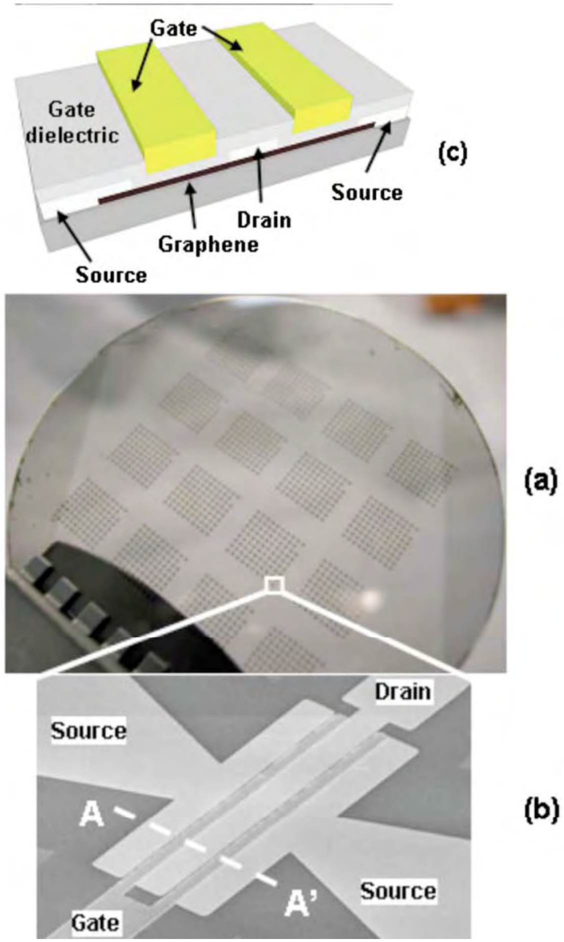
K. S. Novoselov, et al., Nature (2005)

Disadvantage of graphene
1. Low on/ off ratio
2. Usually P-type in air
3. Bad air stability

Graphene Transistor (on SiC) top-gated



[20] S. Hertel et al., *Nat. Commun.* **3**, 957 (2012)

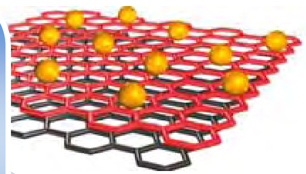


IBM wafer-scale epitaxial graphene

Effects on Transport Properties

Charge impurities

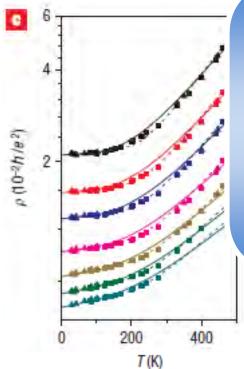
(Doping, Absorbate)



Yu, W. *etal. Nano Lett.* (2011)

Phonon Scattering

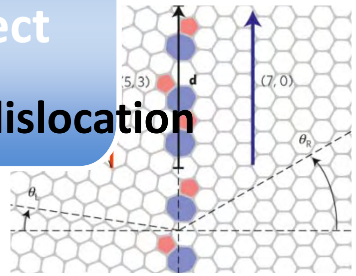
(Temperature)



J.–H. Chen,*et al,* Nat. Nanotechnol.(2008)

Intrinsic Defect

Grain boundary, dislocation

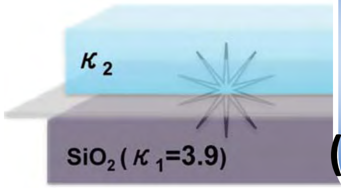


Oleg V. Yazyev, Steven G. Louie. Nat. Mater. (2010)

Could be modified

Environmental Condition

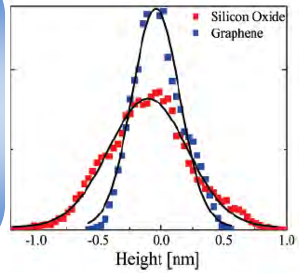
(Atmosphere, Dielectric)



F. Chen.*et al.* Nano Lett. (2009)

Surface Roughness

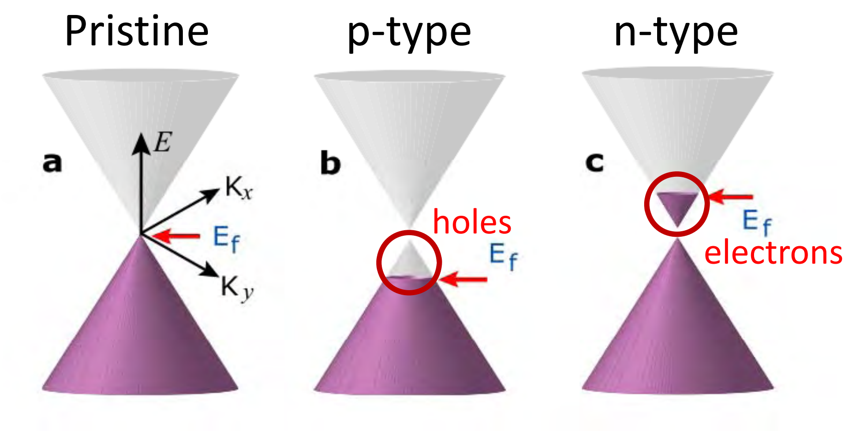
(Substrate)

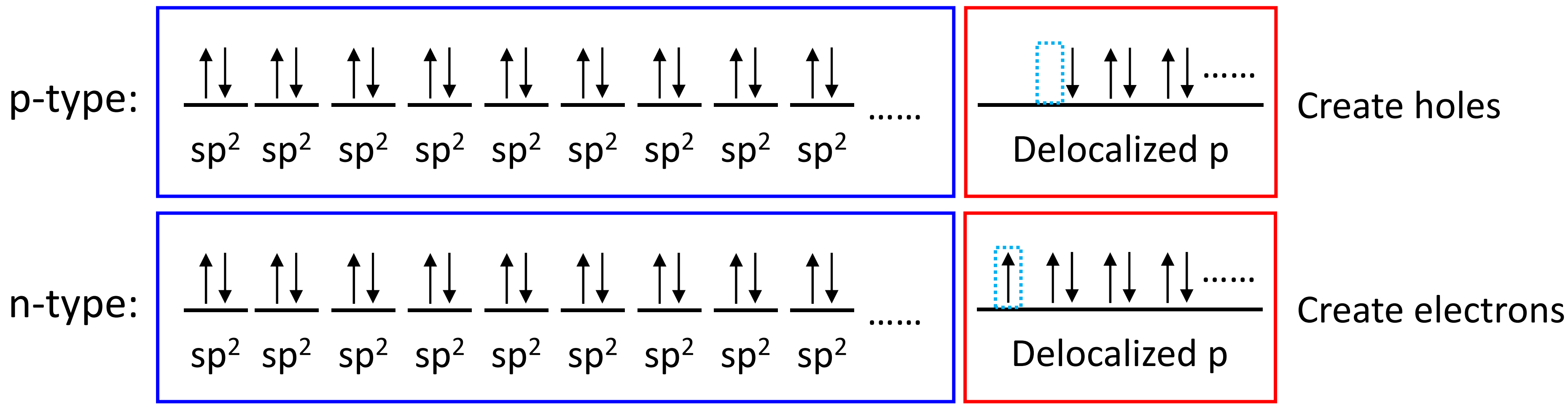


Ishigami, M. *et al.* Nano Lett. (2007)

Doped Graphene by heteroatoms

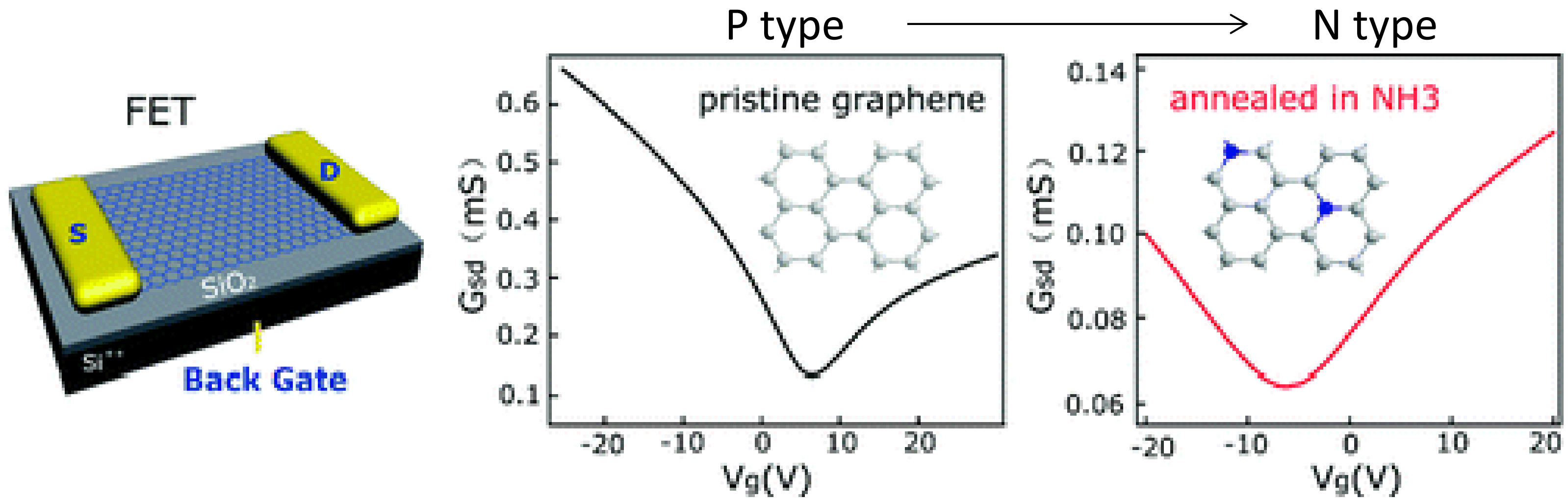
- Doping by heteroatoms
  - p-type doping
  - n-type doping





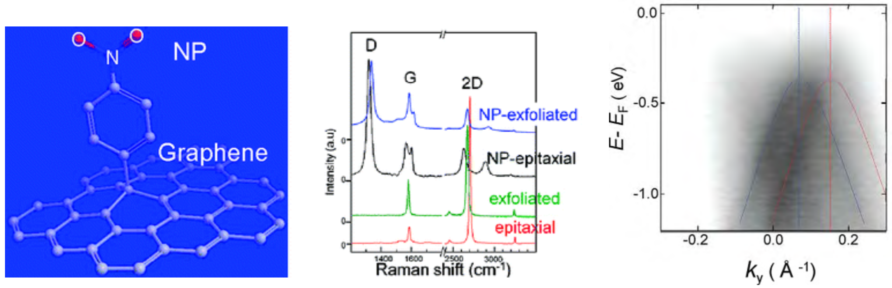
Doped Graphene by chemical modification

- Doping by chemical modification
  - Charge transfer
  - Molecules adsorb on graphene, acting as donors or acceptors
  - Epitaxial graphene can be doped by the substrate

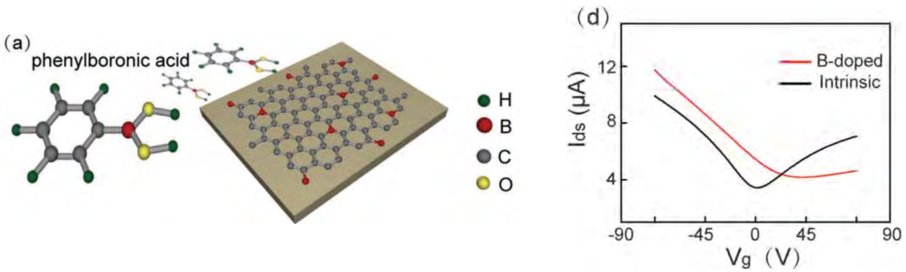


p-type doped graphene

1. Covalent functionalized or substitutional doping

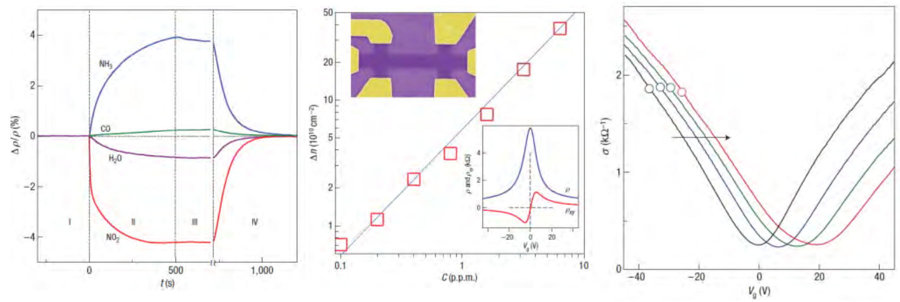


Nano Lett. *10*, 4061–4066 (2010)

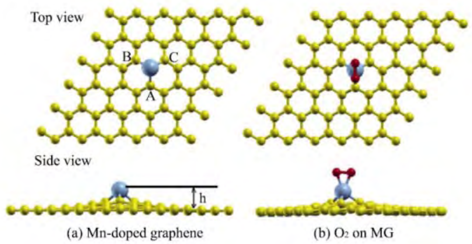


Small, *9,* No. 8, 1316–1320 (2013)

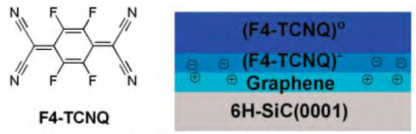
2. Surface charge transferred doping



Nat. Mater. **6**, 652 - 655 (2007)



Phy. Rev. B, 81, 165414 (2010)

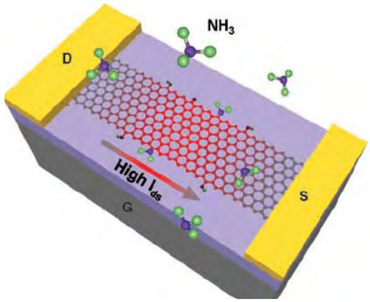


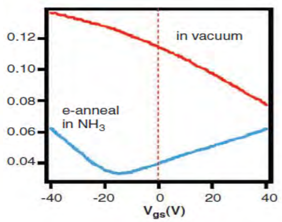
J. Am. Chem. Soc. 129, 10418-10422 (2009)

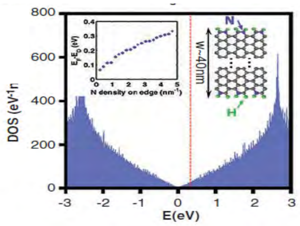
- Covalent functionalized and substitutional doping => destruction of sp2, low mobility
- Surface charge transfer => Graphene is vulnerable to atmosphere

n-type doped graphene

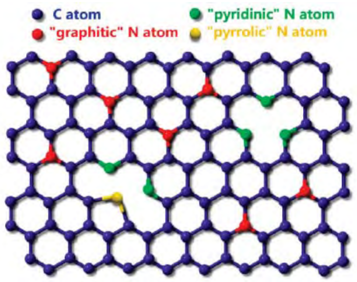
1. Covalent functionalized or substitutional doping

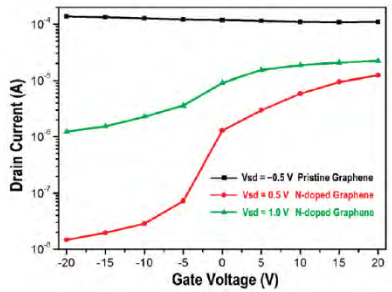






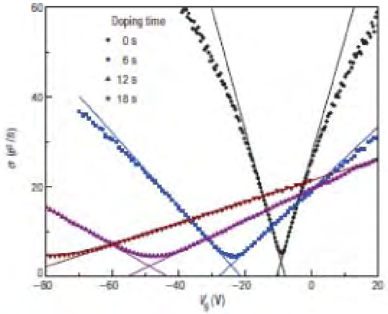
Science 324, 768 (2009)



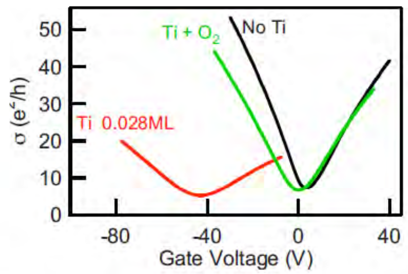


Nano Lett. 9, 1752 (2009)

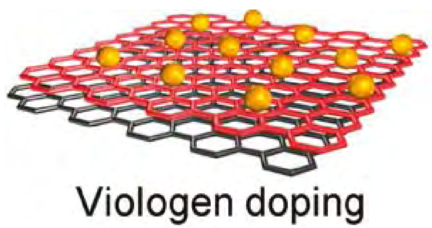
2. Surface charge transferred doping



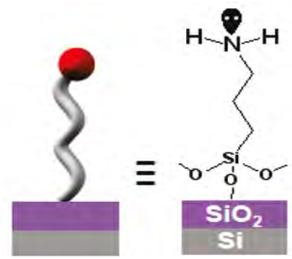
Nat. Phys. 4, 377 - 381 (2008)



***Appl. Phys. Lett.* 98**, 192101 (2011)



Nano Lett. 11, 4759–4763 (2011)

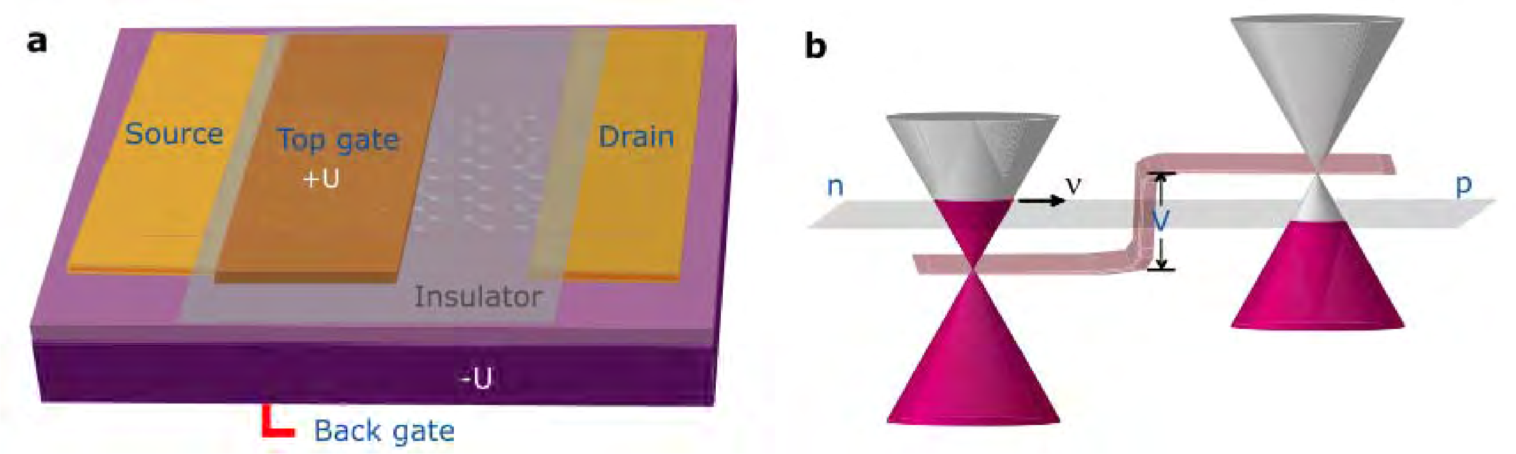


J. Phys. Chem. Lett. 2011, 2, 841–845

- Most of doping methods could considerably damage carrier mobilities of graphene.
- The doping level could not easily be easily controlled.
- The doping devices are very vulnerable to environment, especially for n-type doping.

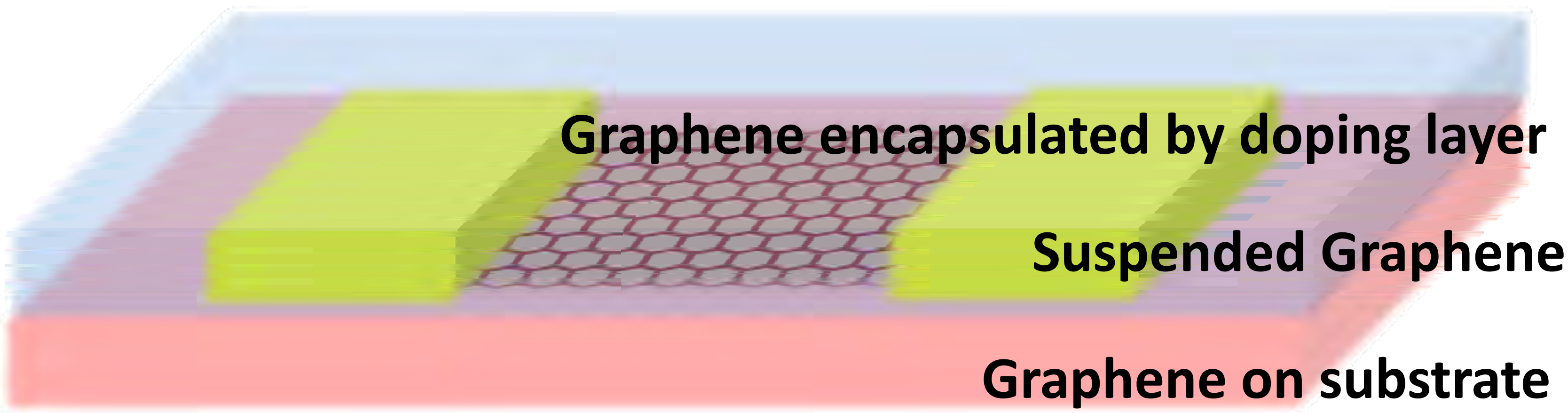
Doped Graphene by electric field

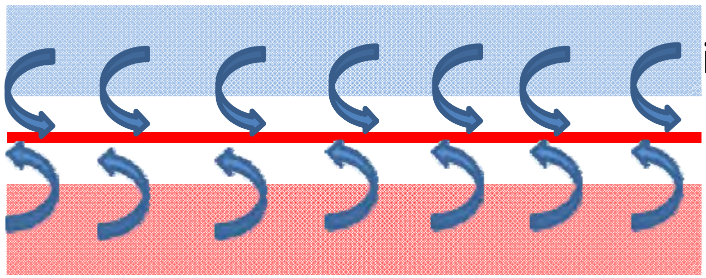
- Doping by electric field
  - Use electric field to shift the Fermi level of graphene



B. Guo et al., *Insciences J.* **1** (2), 80 (2011)

How to improve mobility or control the carrier types in graphene ?





Bottom layer - Substrate

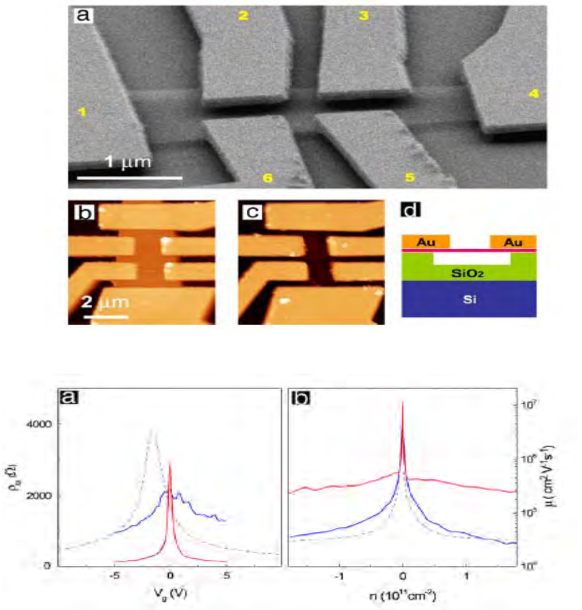
1. **Charge impurity**
2. **Surface Roughness**

Top layer - Encapsulated layer

1. **Charge transfer (doping)**
2. **Preventing from atmosphere**

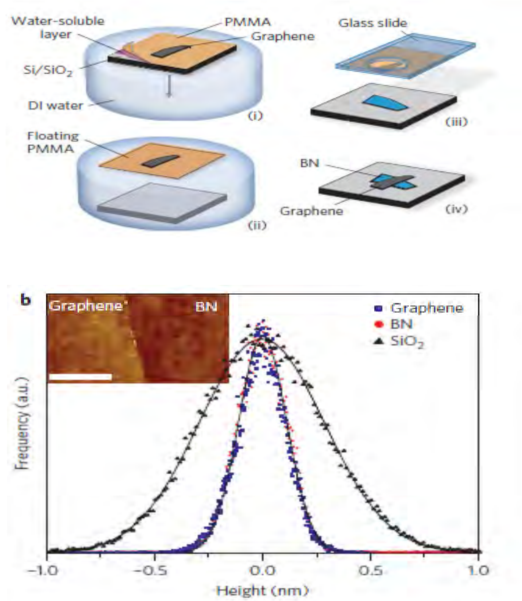
Substrate-dependet transport

1. Suspended Graphene



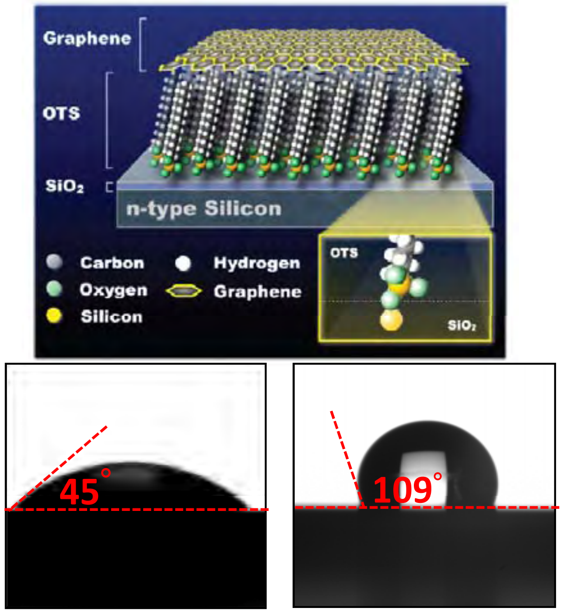
Solid State Commun. 146, 351-355 (2008)

2. Graphene on Boron Nitride



Nat. Nanotechnol. 5, 722–726 (2010)

3. Graphene on organic functionalized substrate



Nano Lett. 2012, 12, 964–969

- Suspended Graphene

1. highest mobility
2. nearly ballistic transport
3. difficult to fabricate
4. Can not scale to large area

- Graphene on h-BN

1. high mobility
2. Difficult to fabricate
3. Can not scale to large area

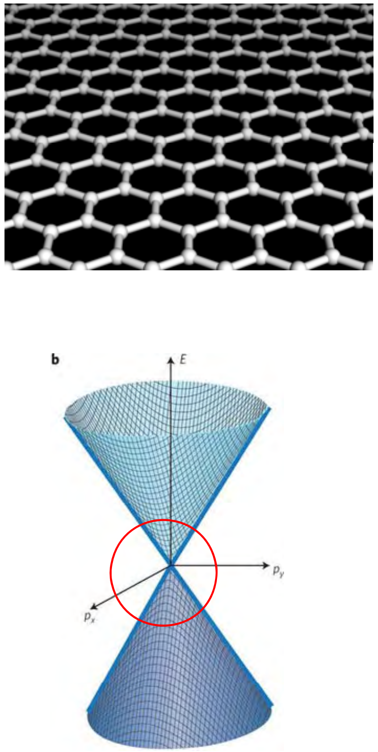
- Graphene on organic functionalized substrate

1. high mobility
2. Easy to fabricate
3. Scalable

Bilayer graphene and Gap Opening

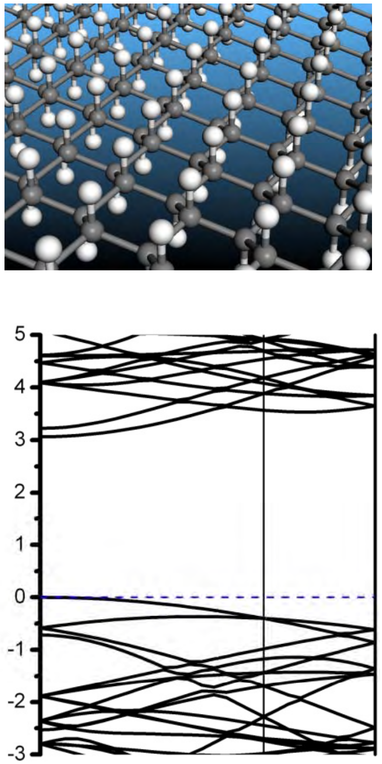
Gap opening

Graphene (sp^2)



No band gap

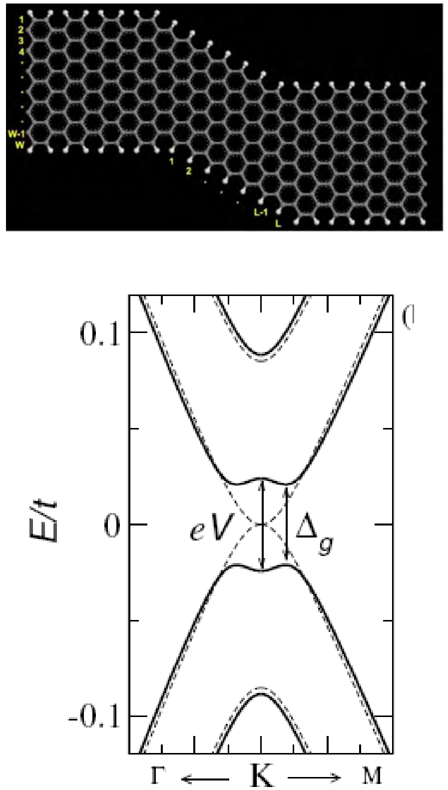
Graphane(sp^3)



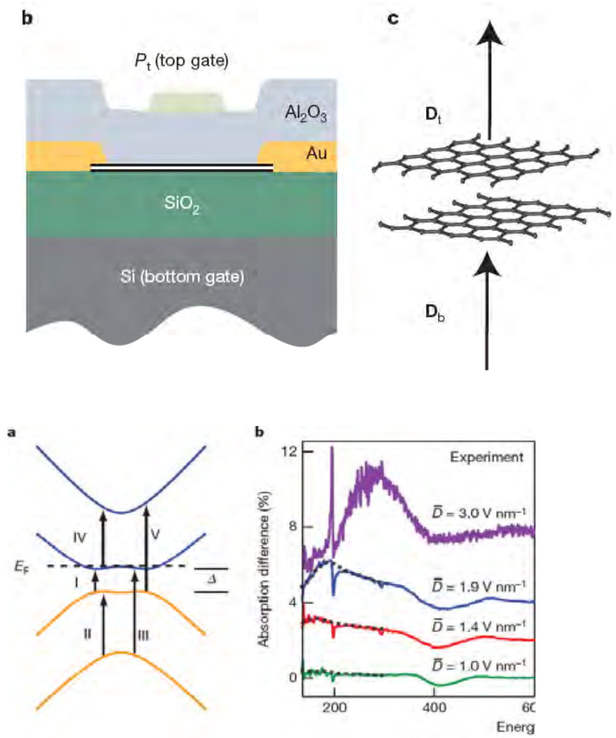
Wide band gap

Elias et al,
Science, 323,5914,2009

Graphene ribbon



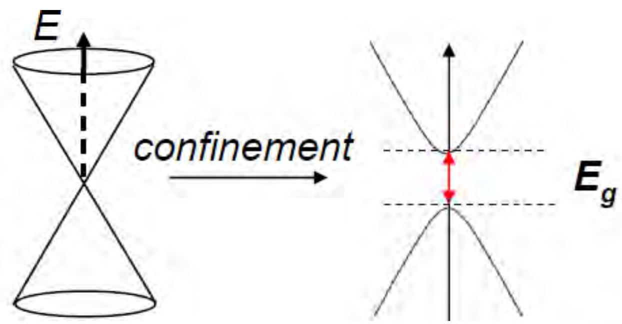
Under applied E field

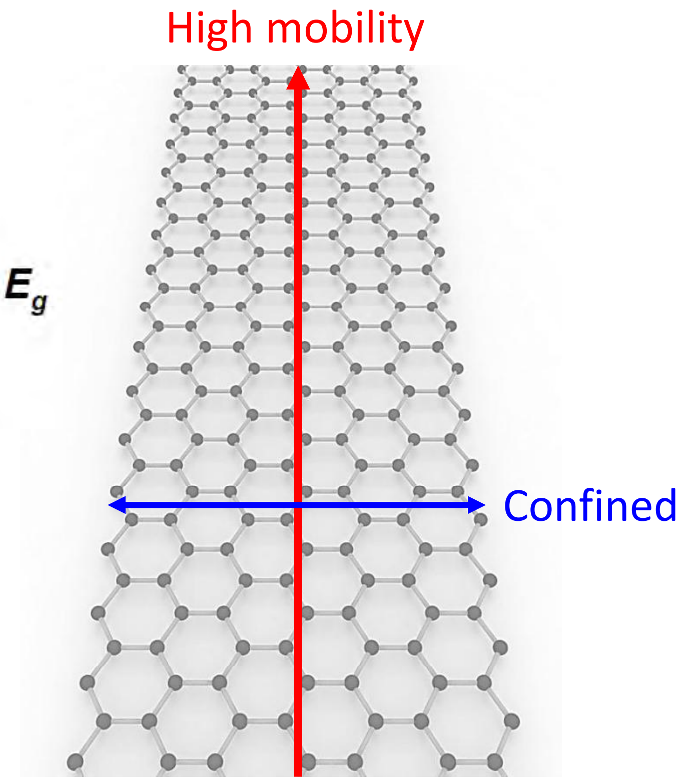


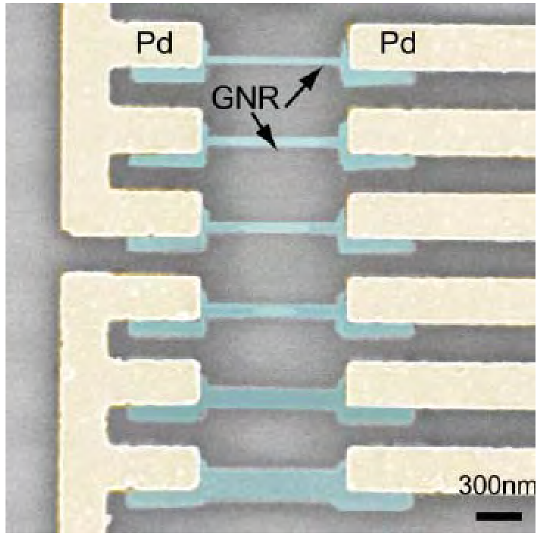
Nature, 2009,Vol.459,p820

Electronic Structures of GNRs

- **Open a gap in graphene-graphene nanoribbon (GNR)**
- **High mobility along the specific direction**
- **Quantum confinement effect**



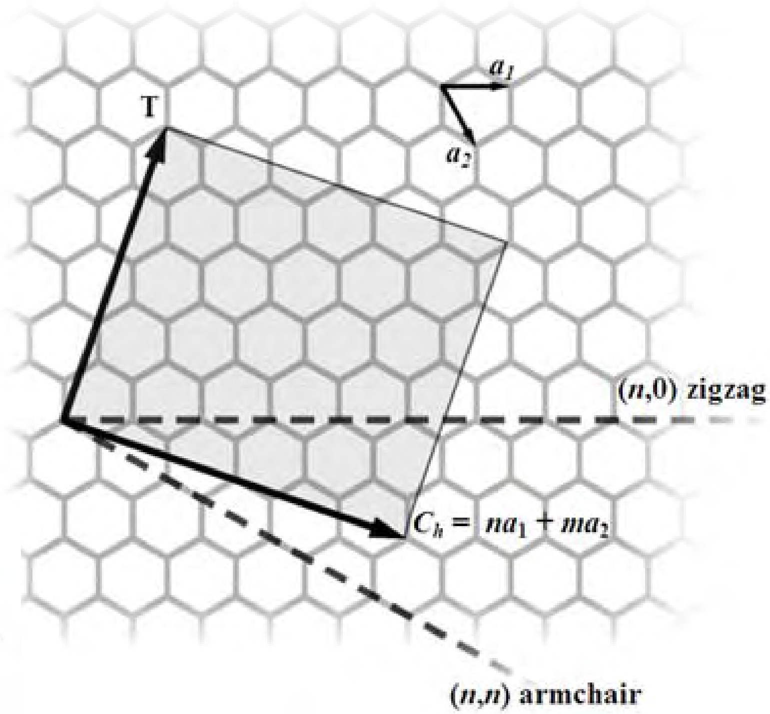


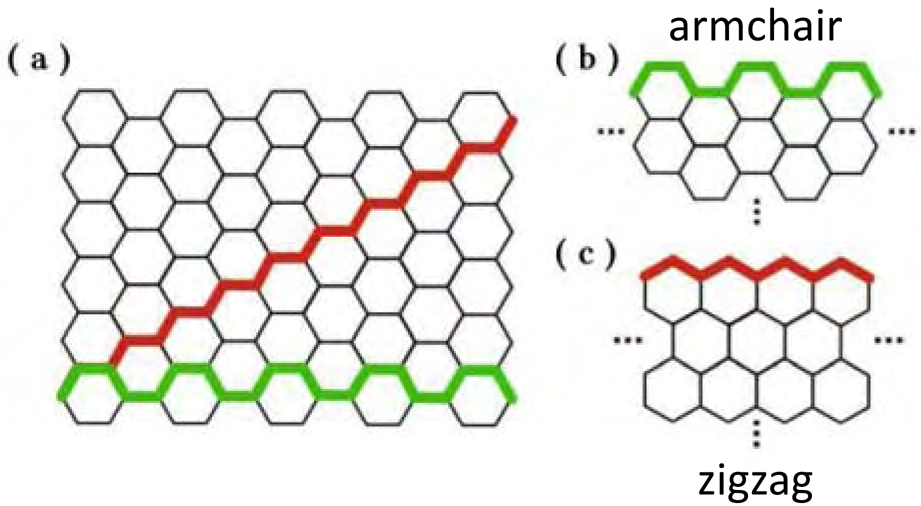


Physical E, 40, 228, (2007)

Graphene Nanoribbon (GNR)

- Structure
  - Graphene strips
  - Charity
    - Two types of edge

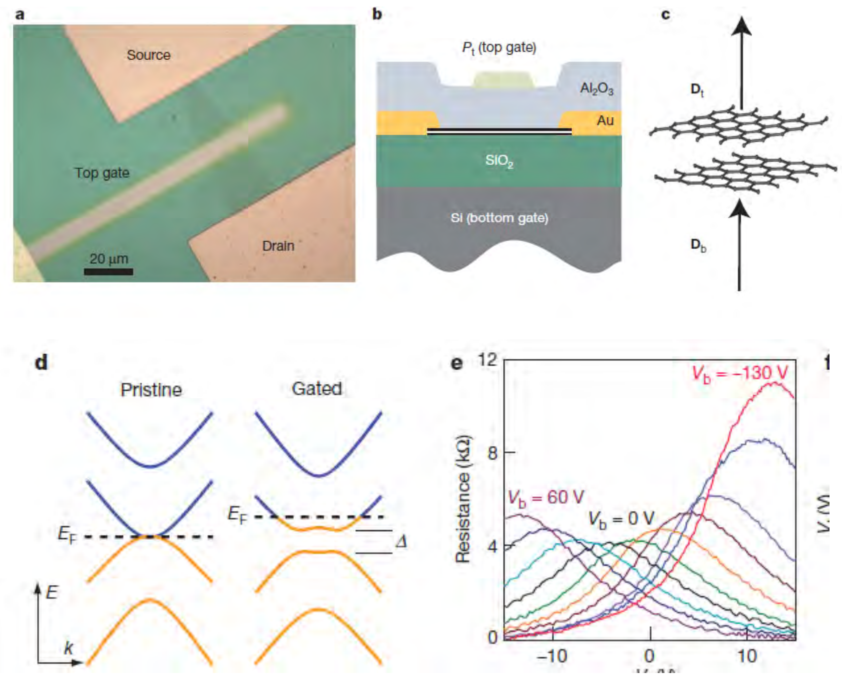




Some of armchair GNRs are semiconucting
metallic: n = 3m+2
semiconducting: n = 3m or 3m+1

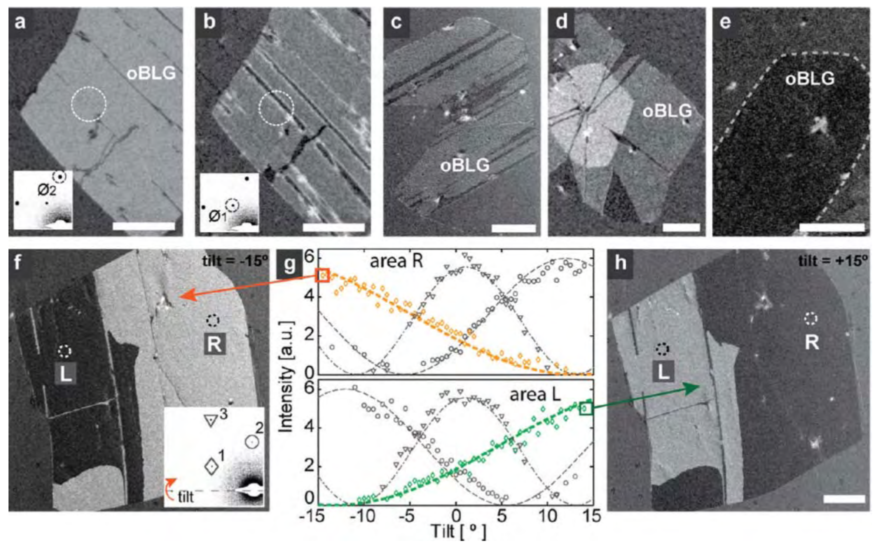
Gap-opening of Bilayered-graphene

Mechanically exfoliated garpehene



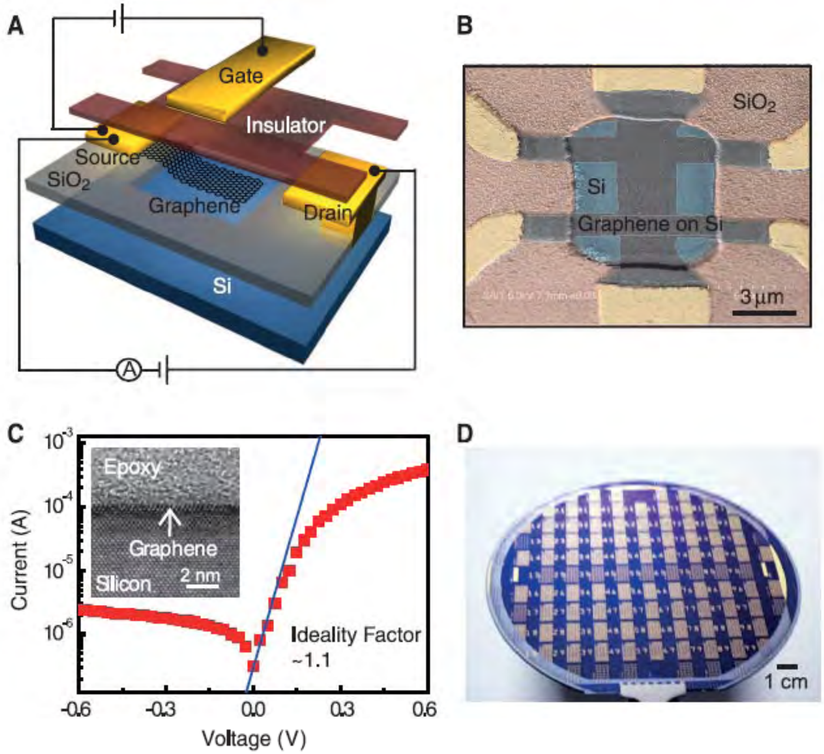
Nature, 2009,Vol.459,p820

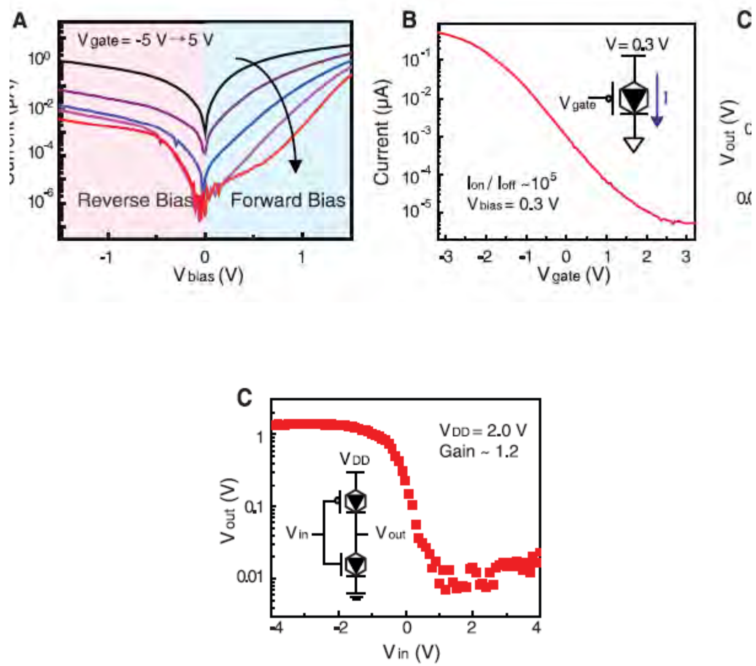
CVD-graphene



Nano Letters, 2012,12, 1609

Graphene Barristor- a gate controlled Schottky barriar

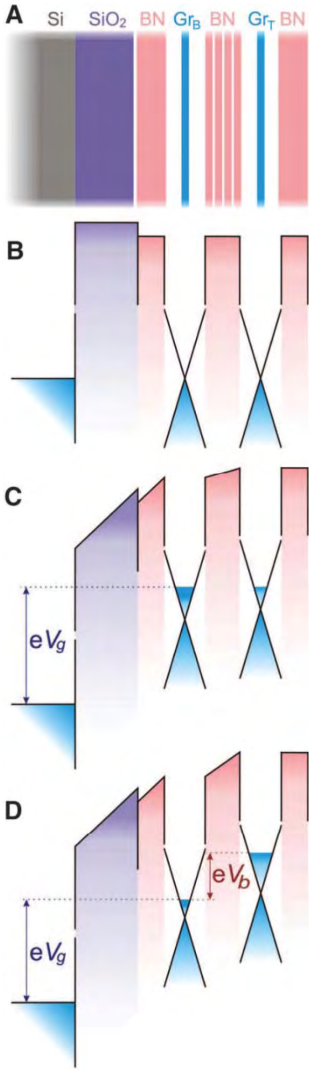


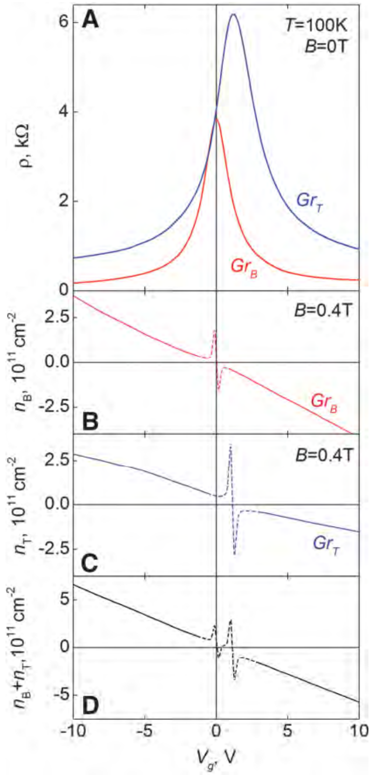


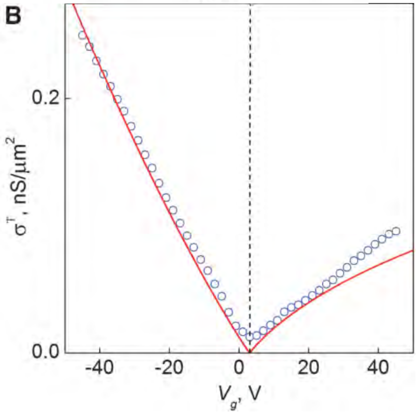
Adjusting graphene workfunction
High on/off ratio~ 10^5

Yang et al, Science, Vol. 336, 1140, 2012

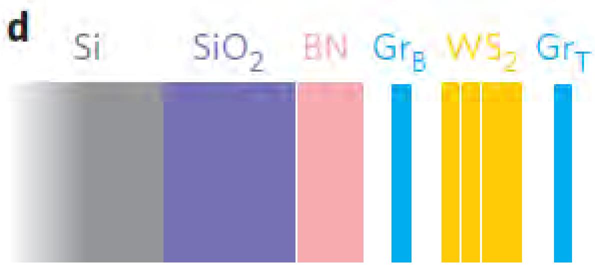
Vertical transnsitor

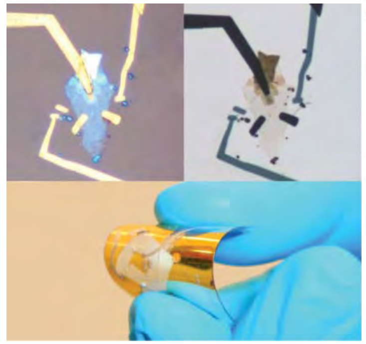


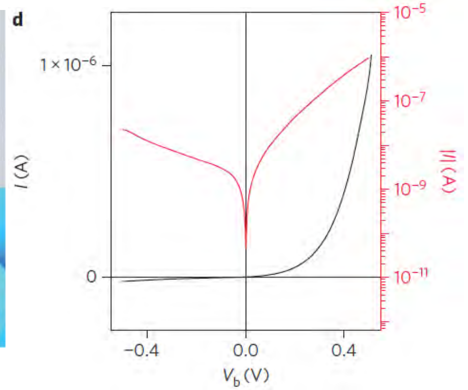




Science, 335 947-950 (2012)







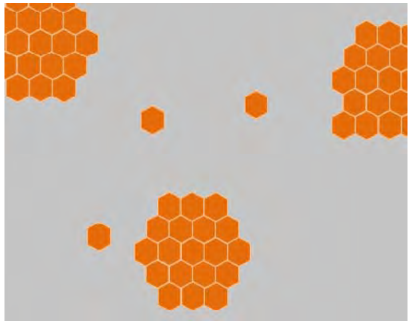
Nature Nanotechnol. 8, 100–103 (2013)

- Combine kinds of 2-D material
- Control tunneling barrier through ultra-thin barrier
- Very Difficult to fabricate

Tunable conduction in graphene based materials

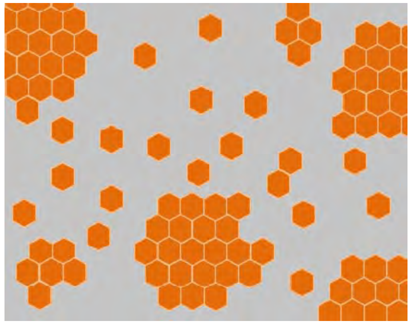
GO

Highly sp^3



Reduction

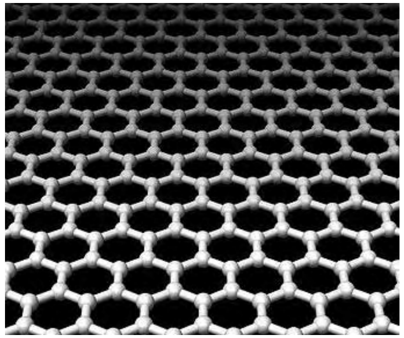
r-GO



10^3 ~ 10^5 Ω/sq

Graphene

Pure sp^2



<100 **Ω/sq**
at 90% T

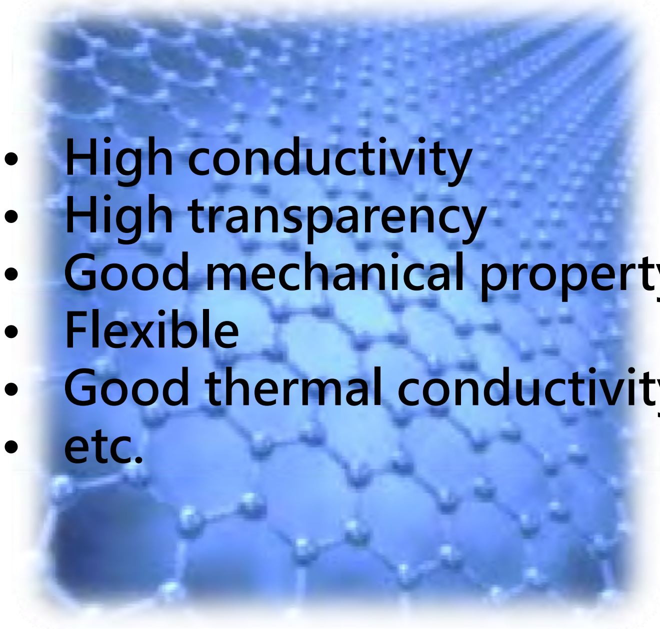
Insulator → **Conductor**

Thin tunneling barrier

Transparent conducting electrode

Next generation production ?

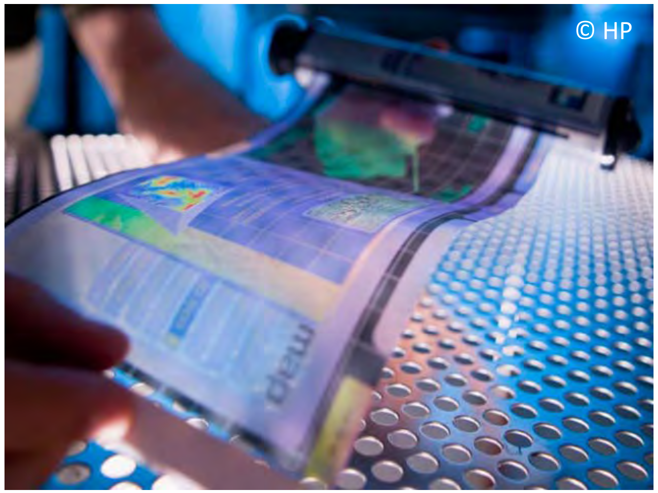
© NOKIA



- High conductivity
- High transparency
- Good mechanical property
- Flexible
- Good thermal conductivity
- etc.

Household appliances

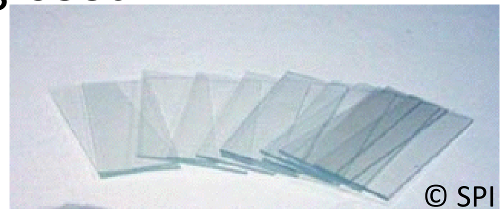
Communication production

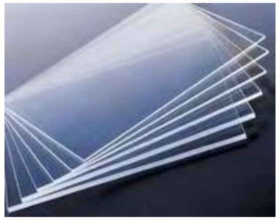


E-paper

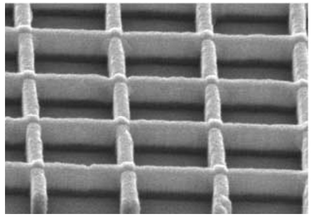
Conventional Transparent Electrode

- **ITO (Indium Tin Oxide)**
  - Scarcity of indium and high manufacturing cost
  - Vacuum process
  - Relatively brittle

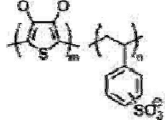




- **Alternative :**
- Conducting oxides
  - Al doped ZnO

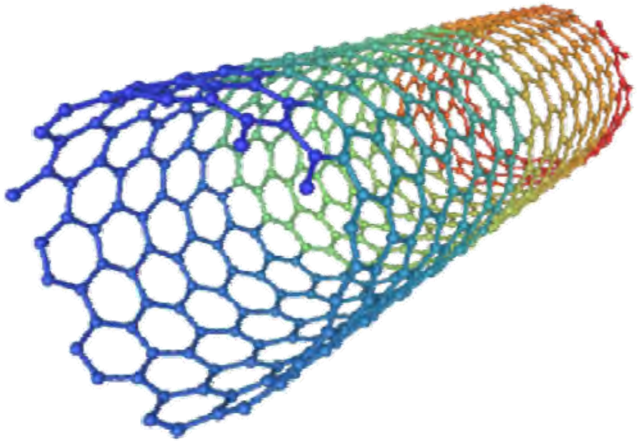


- Metal wire mesh
  - Ag nanowire, Cu grid
- Conductive polymer, PEDOT:PSS



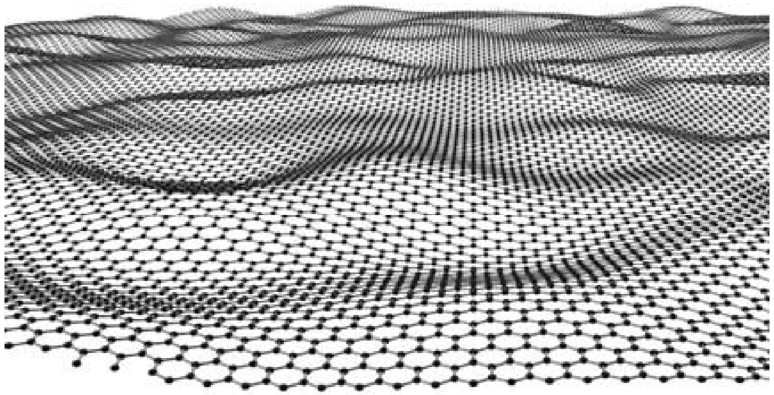
Low Dimensional Nanocarbon Materials

Single walled carbon nanotube (ID)



- 1-D material
- Metallic and semiconducting
- High carrier mobility (120,000 $cm^2V^{-1}s^{-1}$)
- High current carrying capacity
- Excellent mechanical strength

Graphene (2D)



- sp^2 bonded carbon
- 2-D honeycomb crystal lattice
- High carrier mobility (200,000 $cm^2V^{-1}s^{-1}$)
- Low electrical resistivity (10^{-6} Ω·cm) (< siliver)
- Good mechanical properties

List of various end applications, their key features, and the suitability of each material

Application	Key Features	Nanotube	Graphene	Metal Nanowires
Touch Panels	Flexibility	o	o	x
	Patterning	o	o	o
	Sheet resistance	o	-	o
	Transparency	-	-	o
LCD	Surface roughness	-	o	x
	Ionic impurities	x	x	x
	Conformal Coating	o	o	x
	Color/Haze	o	o	x
OLED/Solar Cell	Work Function	o	o	x
	Sheet resistance	x	x	o
	Surface Roughness	-	o	x
	Stability	o	o	x

("o" = superior, "-" = good, "x" = poor).

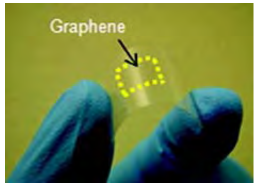
Hecht, D. S. et. Al., *Adv. Mater.* **2011,** ***23,*** 1482–1513

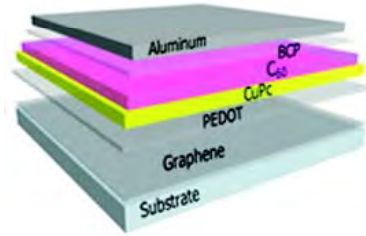
- **Transparent conducting electrode**

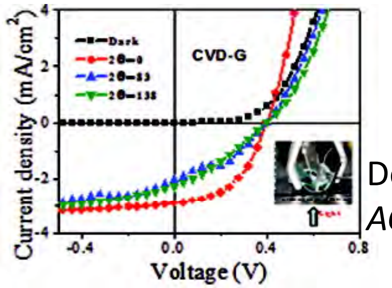
Touch Panel

Bae, S. *et al.*
Nature Nanotech. ***4, 574–578 (2010).***

Solar Cell

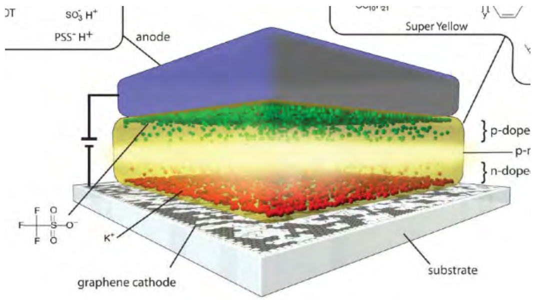


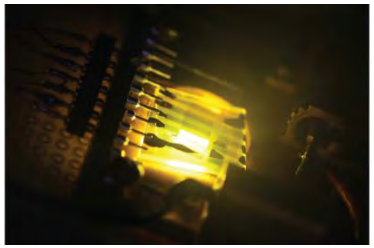




De Arco, L. G. *et al*
ACS Nano **4, 2865–2873 (2010)**

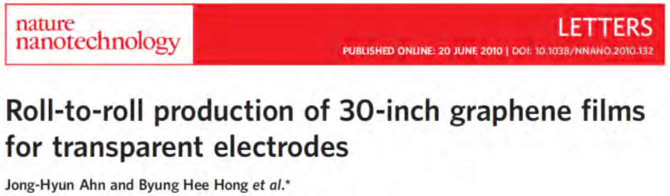
Light Emitting Diode





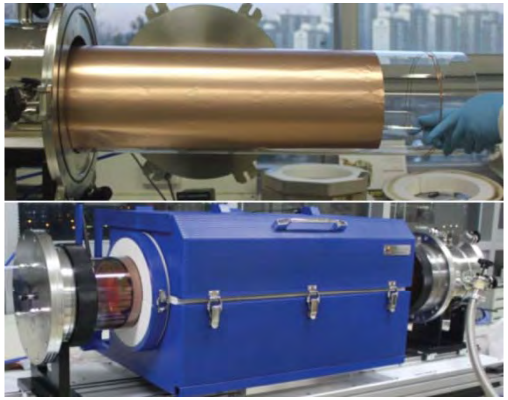
Matyba, P. *et al.*
ACS Nano ***4, 637–642 (2010).***

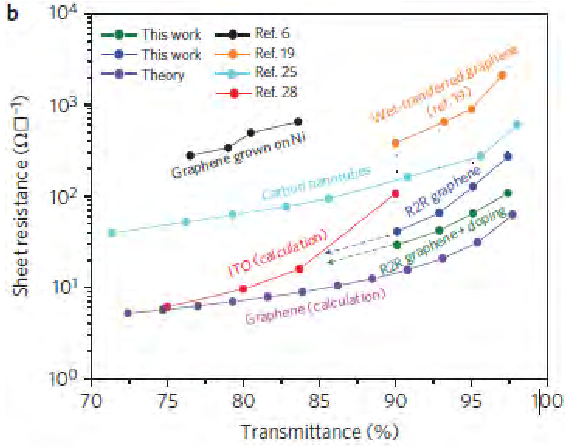
Large area CVD grown graphene for optoelectonic applications

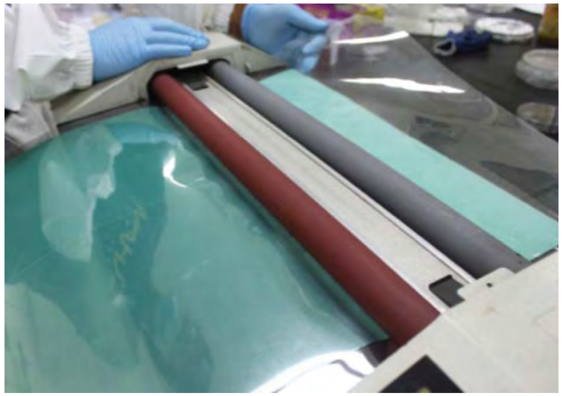

nature nanotechnology | LETTERS
PUBLISHED ONLINE: 20 JUNE 2010 | DOI: 10.1038/NNANO.2010.132

Roll-to-roll production of 30-inch graphene films for transparent electrodes

Jong-Hyun Ahn and Byung Hee Hong *et al.**

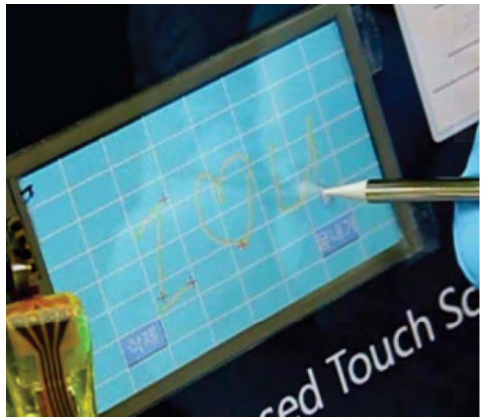






Roller printing

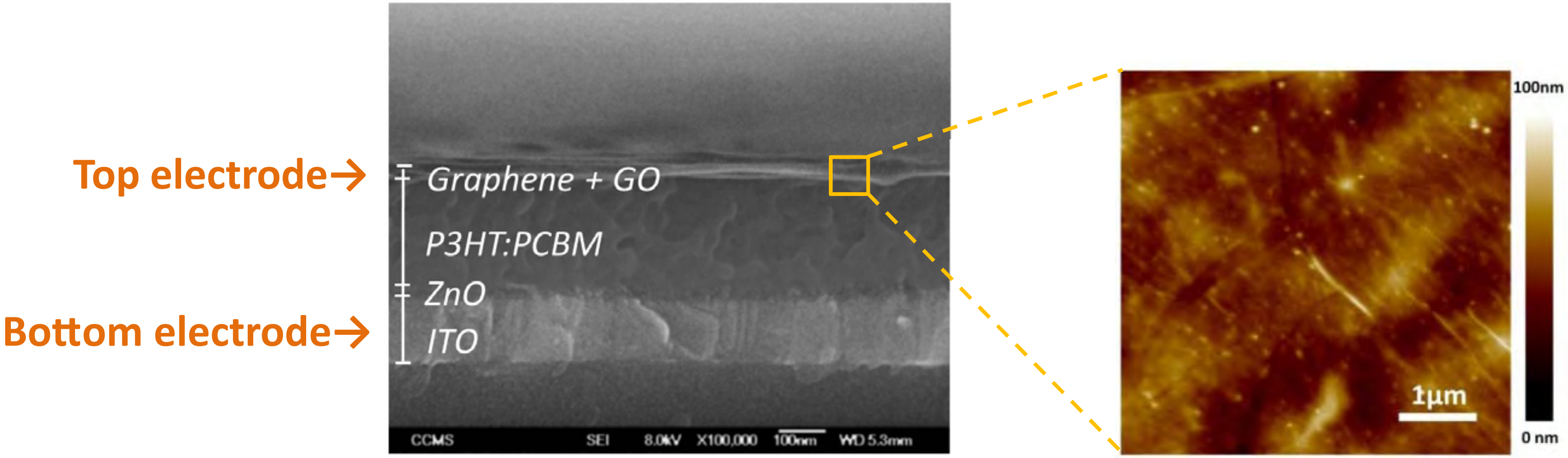
Scale up

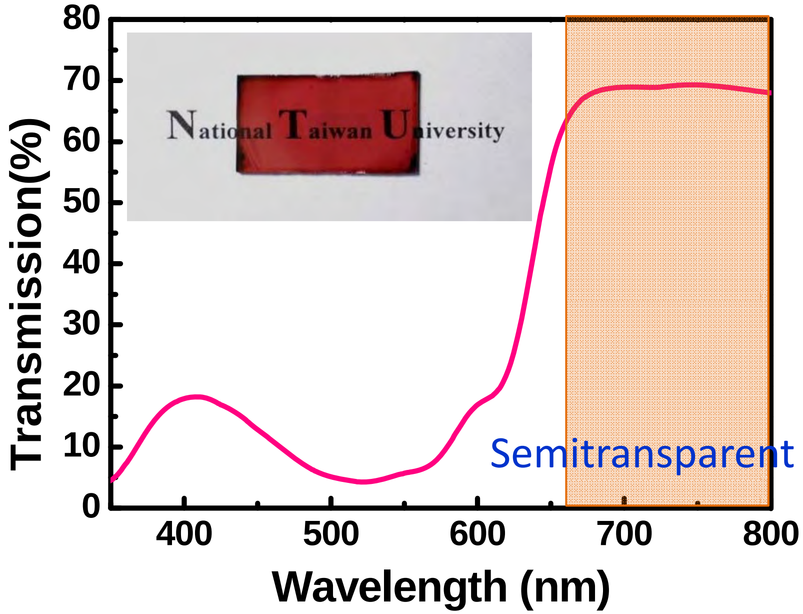


Touch panel

Bae et al. Nature Nanotechnology 5, 574–578 (2010)

Top laminated graphene electrode in a semitransparent polymer solar cell

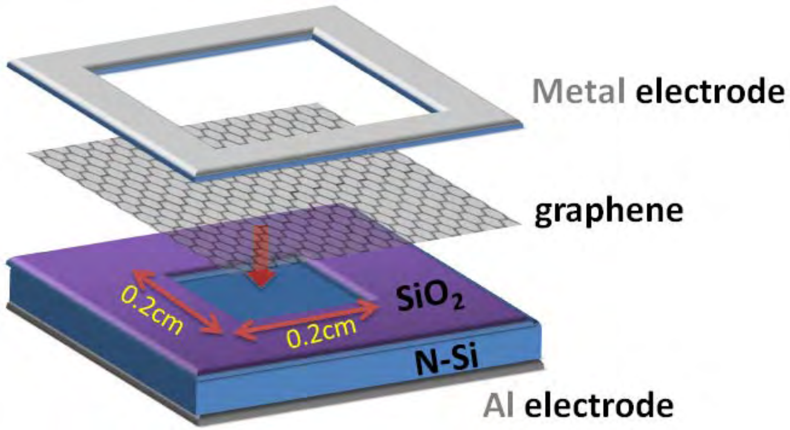


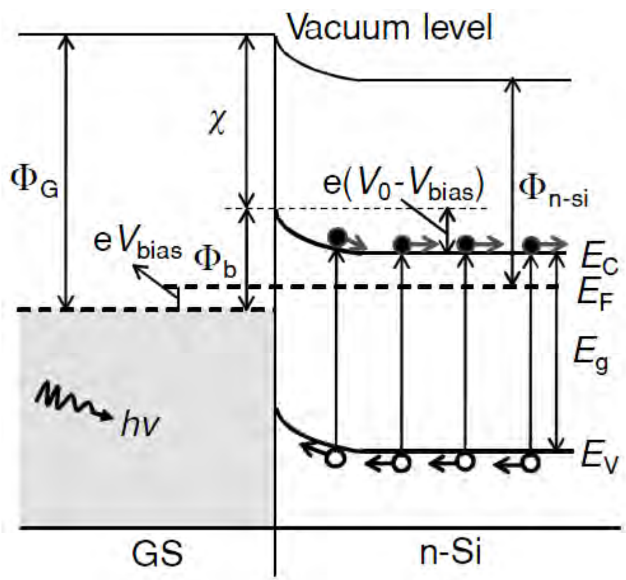


ACS Nano ,Vol.5, 6564, (2011)

Si/Graphene junction solar cell

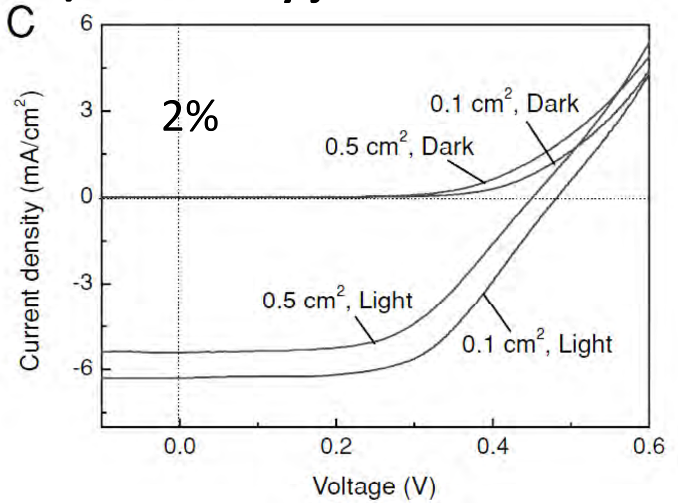
Device structure



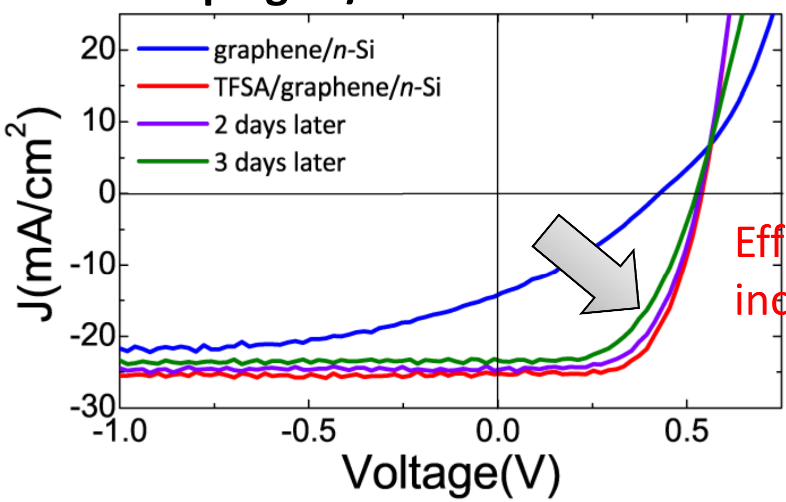


Energy diagram of the forward-biased GS/n-Si Schottky junction

Gr/Si schottky junction solar cell



P doping Gr/Si

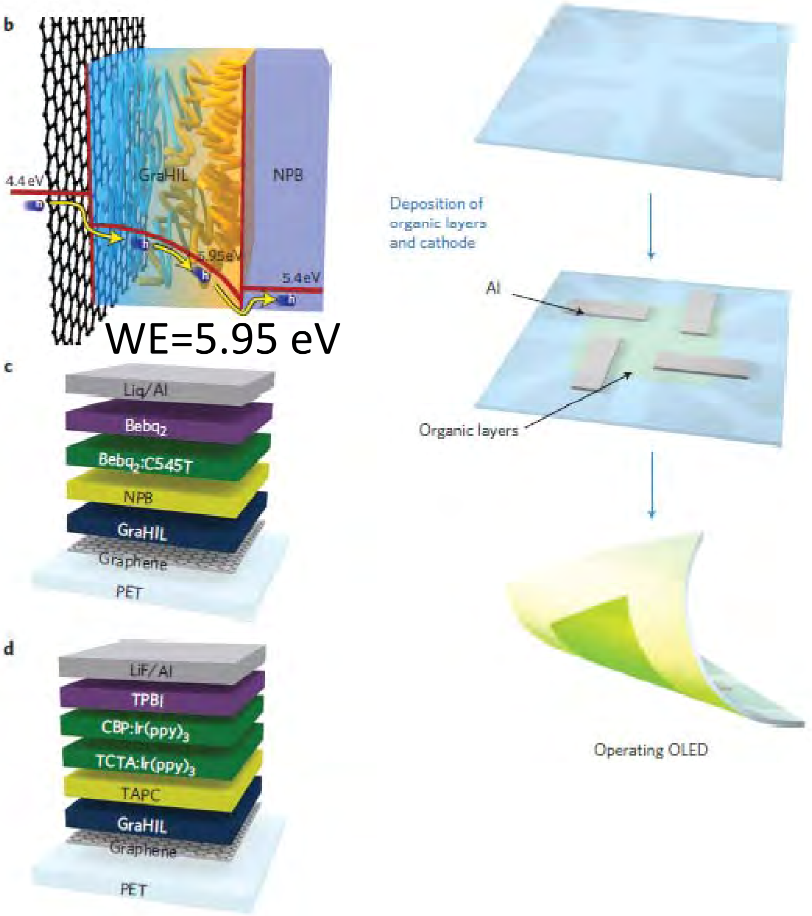


Li. X. et. al., Adv. Mater. **2010**, *22*, 2743–2748

Miao, X. Et. al., *Nano Lett*. **2012**, *12*, 2745−2750

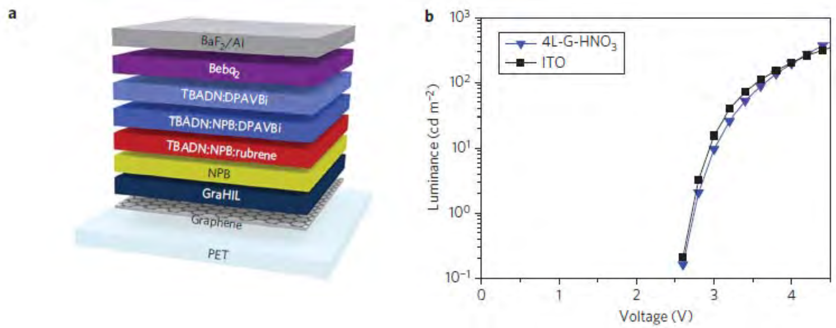
The Future development of large area CVD graphene in OLED applications

4-layered HNO_3 doped Gr~ 30 Ω/□

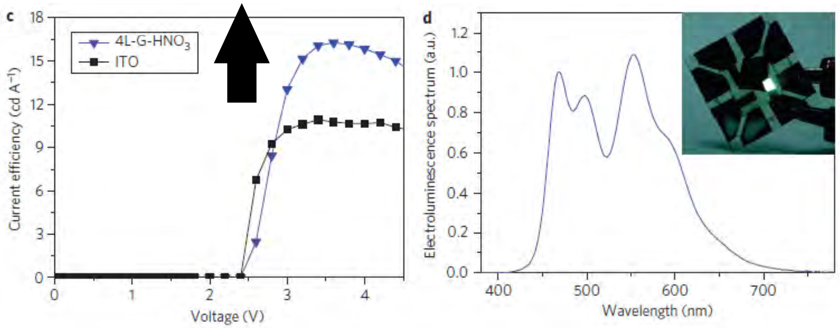


WE=5.95 eV

Gra HIL: Self-organized gradient hole injection layer



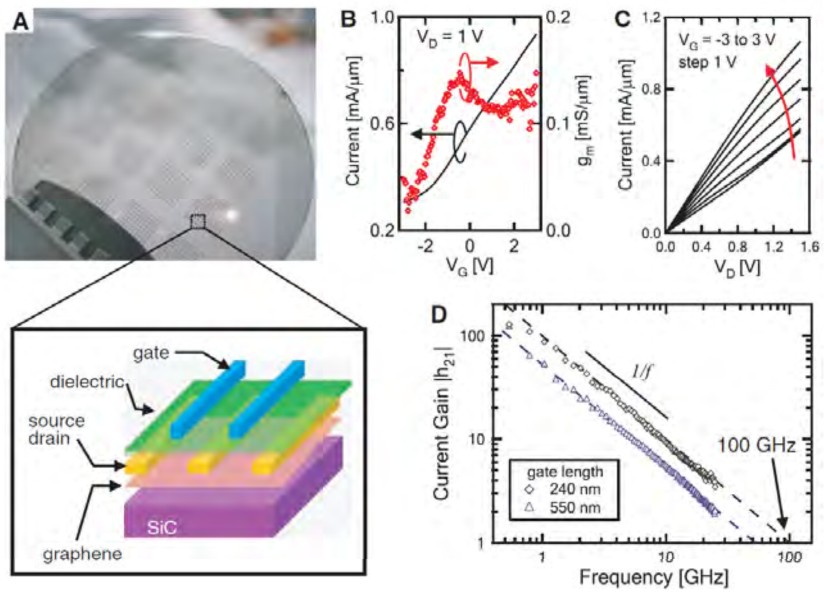
The white OLEDs with the graphene anode exhibited a much higher the ITO anode



T.H. Han, et al., *Nature Photonics,* **6**, 105–110, (2012).

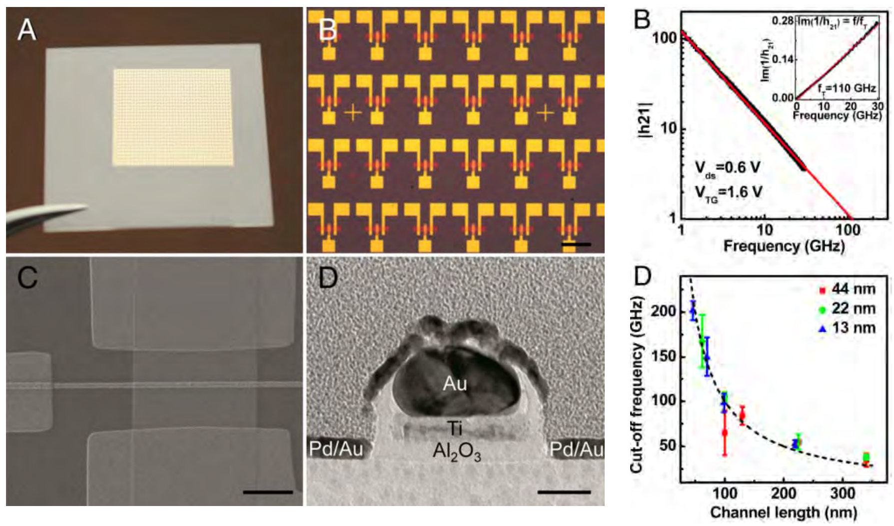
Graphene for other applications

Graphene for Radio Frequency (RF) Transistor



Science, 327 , 662 (2010)

up to 100 GHz (cut-off frequency)



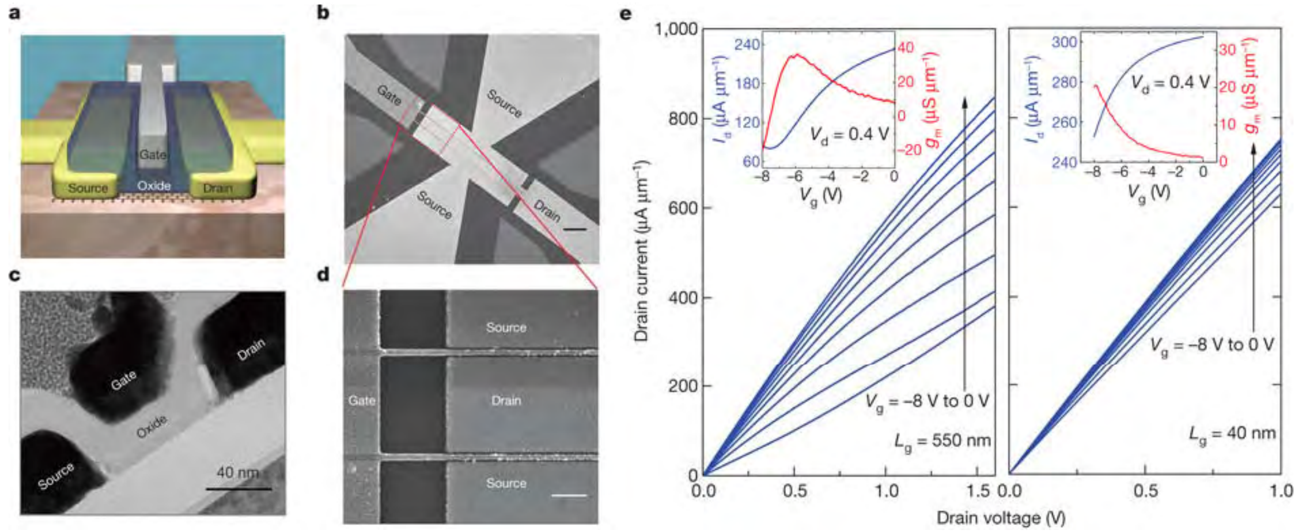
Proc. Natl. Acad. Sci. U.S.A. 109, 11588–11592 (2012)

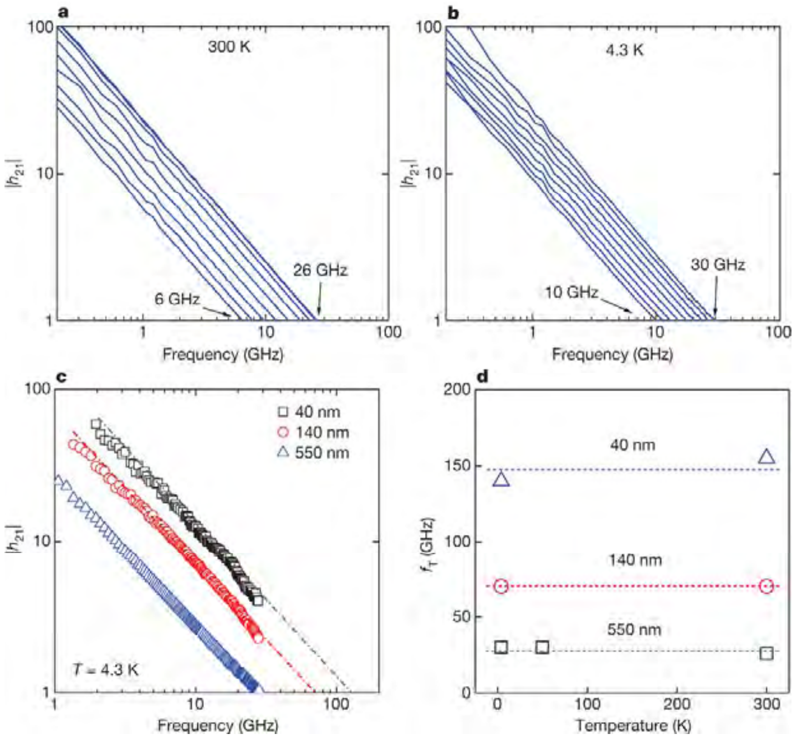
up to 427 GHz

Why use graphene in RF-tech

- Low on-off ratio => fail in CMOS tech
- High mobility, carrier saturation velocity, and large current density=> high cut-off frequency
- High quality graphene => Toward Terahertz regime in the future

High-frequency, scaled graphene transistors on diamond-like carbon



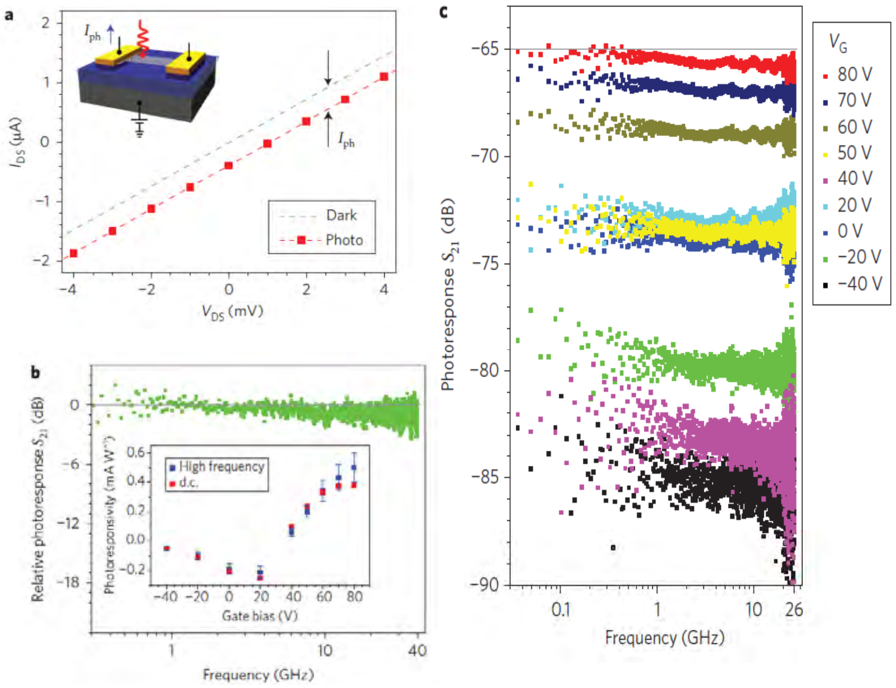


Cut-off frequencies as high as 155 GHz have been obtained for the 40-nm transistors, and the cut-off frequency was found to scale as 1/(gate length).

Wu, Y., et. al. *Nature*, 2011, 472 74–78

Ultra fast and Ultra high gain Photodetector

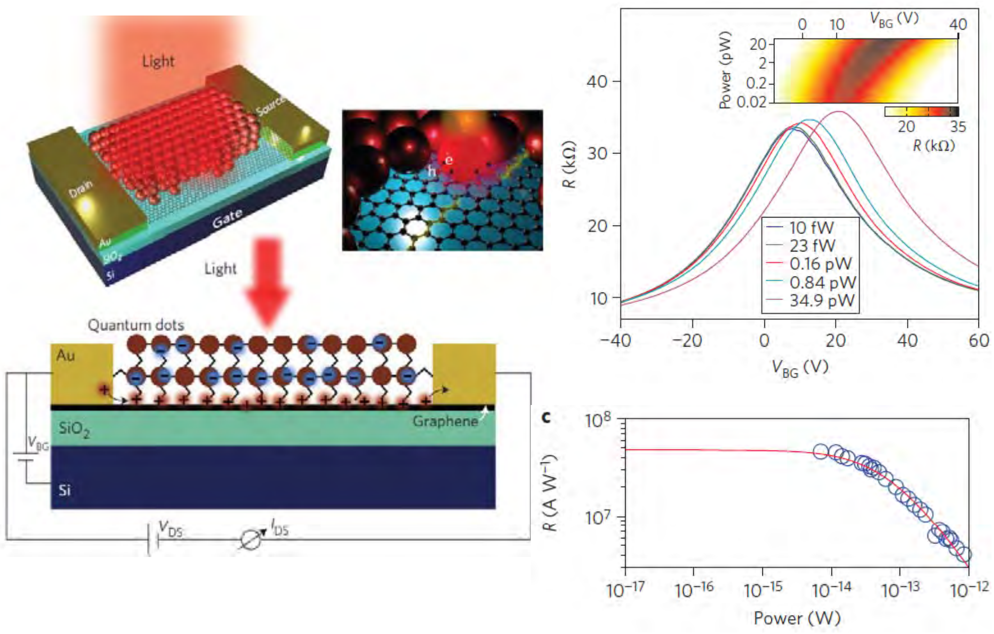
Ultra fast photodectector



Nature Nanotech. 4, 839–843 (2009)

- Light is absorbed by graphene
- P-n junction between channel and graphene covered with metal
- Gate dependent photoresponse
- Could be operated at frequency as high as 40GHz

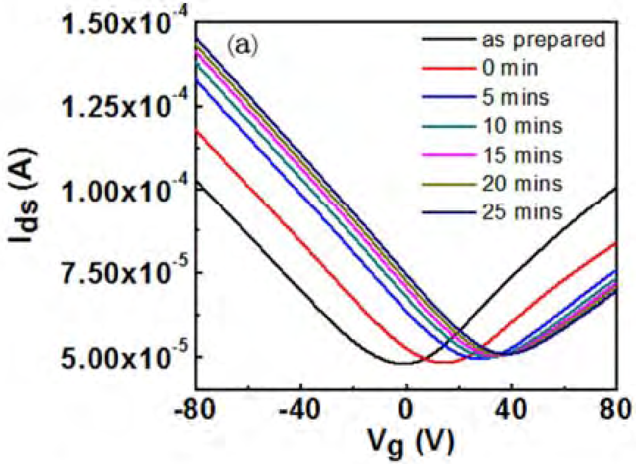
Ultra high gain photodectector

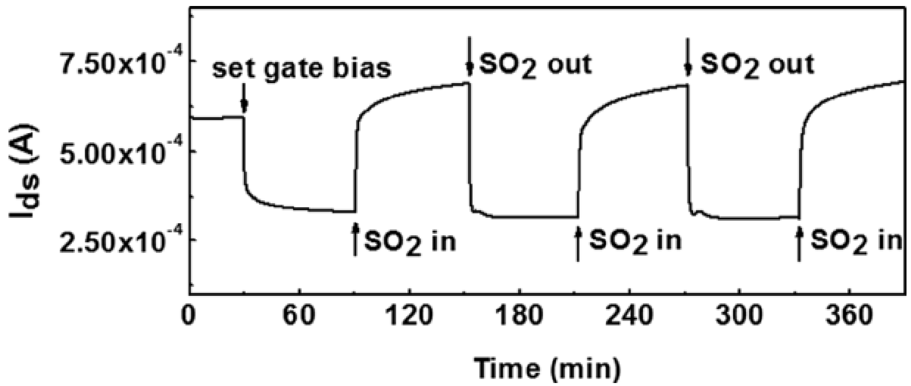


Nature Nanotech. 7, 363–368 (2012)

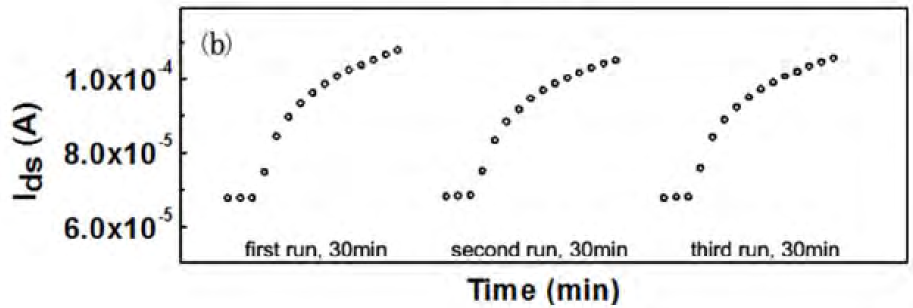
- Light is absorbed by photo-active material on graphene
- Charge transfer from photo-active material to graphene
- Gain could be very large due to inherent high mobility of graphene

Detection of sulfur dioxide (SO_2) gas with graphene field effect transistor





SO_2 strongly p-dopes the graphene

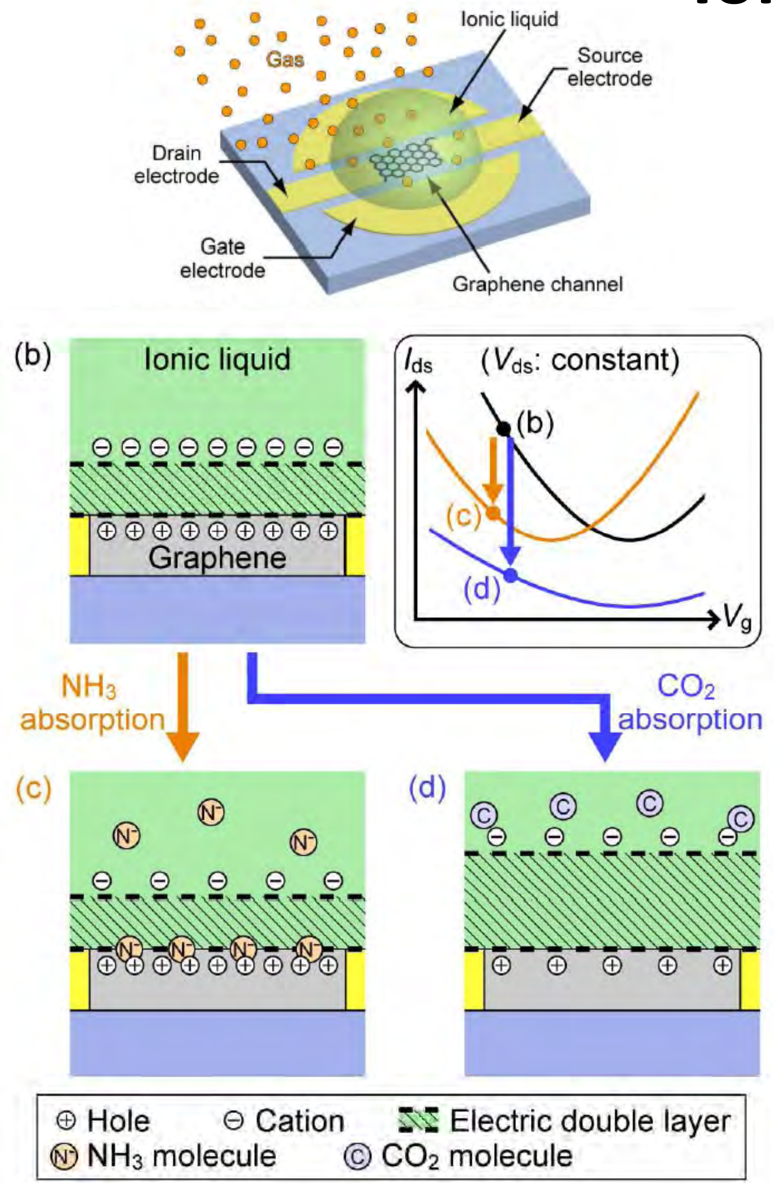


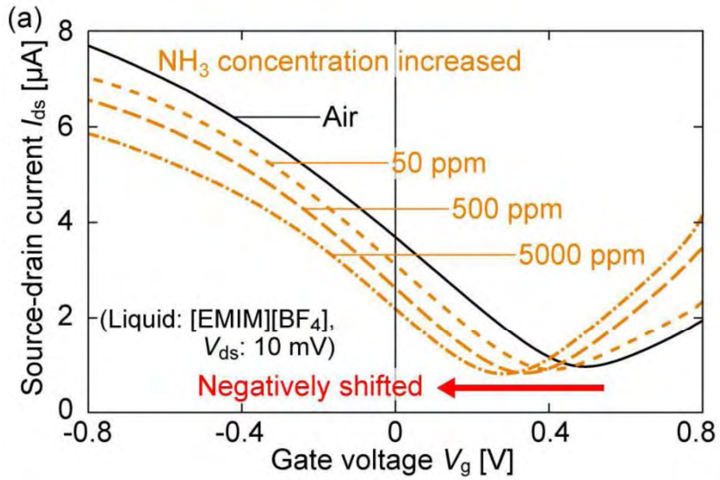
Reproducibility of the graphene FET as a SO_2 gas detector

1. the Dirac point shifted 0.678V/ppm to the positive side
2. the resistance decreased about 60% at a SO_2 concentration of 50 ppm.

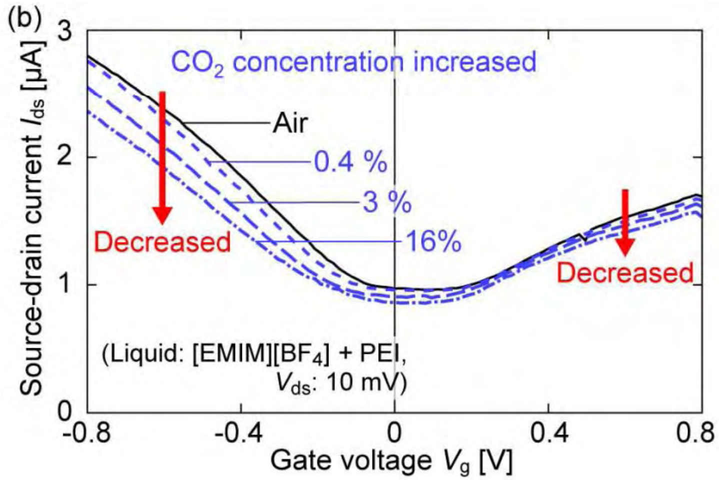
Ren, Y. et. al., Appl. Phys. Lett. 2012, 100, 163114

A Graphene FET Gas Sensor (CO_2, NH_3) Gated by Ionic Liquid





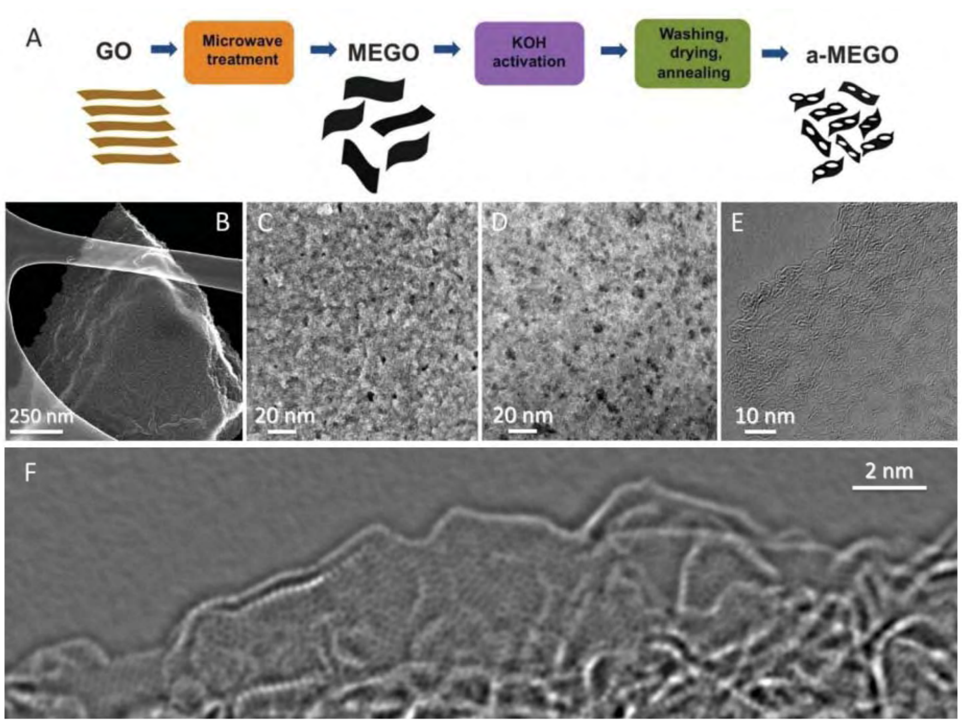
NH_3 molecules transferred negative charge to graphene channel

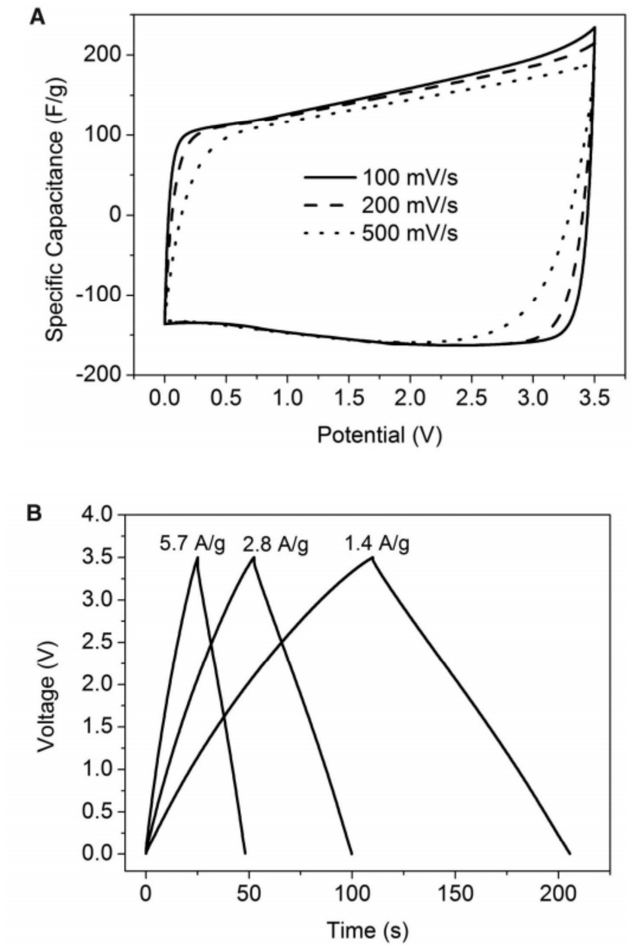


The decrease in I_{ds} over the entire voltage caused by CO_2 denotes that capacitance of the EDL was reduced.

A. Inaba, et. al. IEEE, 2013, 969

Carbon-Based Supercapacitors Produced by Activation of Graphene





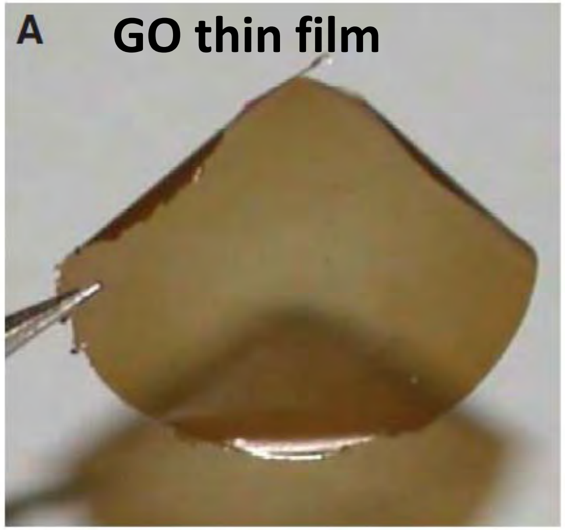
The advantages of MEGO:

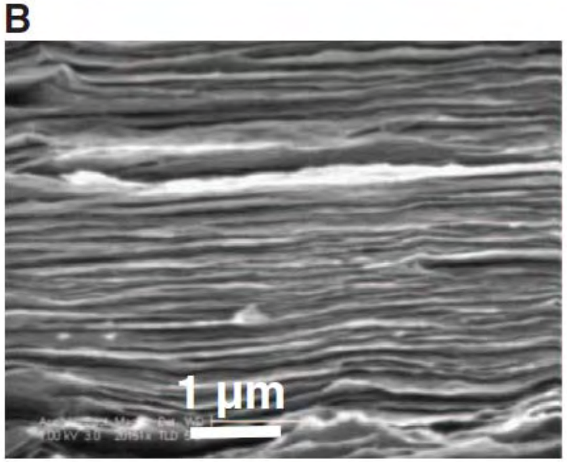
- High electrical conductivity
- Low oxygen and hydrogen content.
- sp^2 -bonded carbon with continuous 3D network

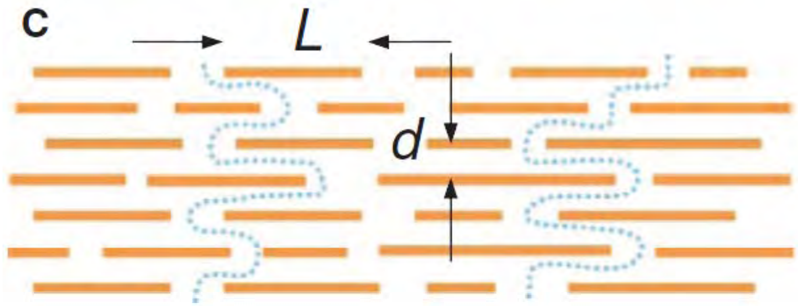
For a packaged cell, the power density of ~75 kW/kg is one order higher than the values from commercial carbon supercapacitors.

Zhu, Y., et. al., Science, 2011, 332, 24

Unimpeded Permeation of Water Through Helium-Leak–Tight Graphene-Based Membranes

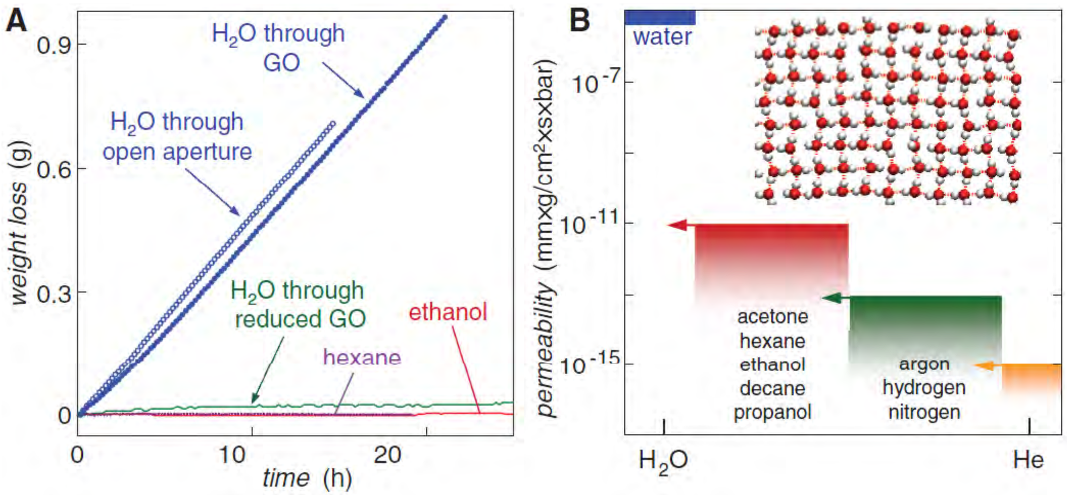






Completely impermeable: liquids, vapors, and gases

Unimpeded permeation: water H_2O

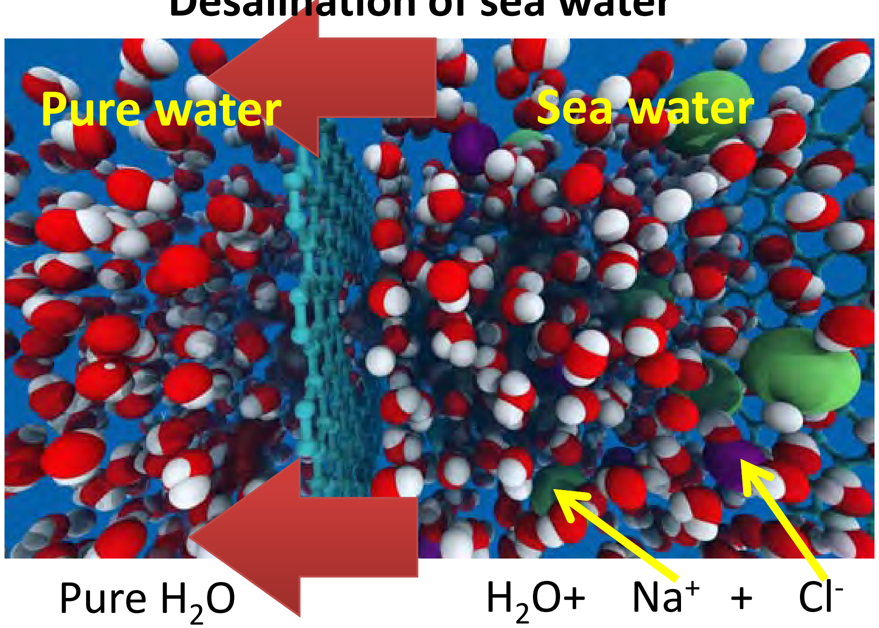


H_2O permeates through the GO at least 10^{10} times faster than He gas

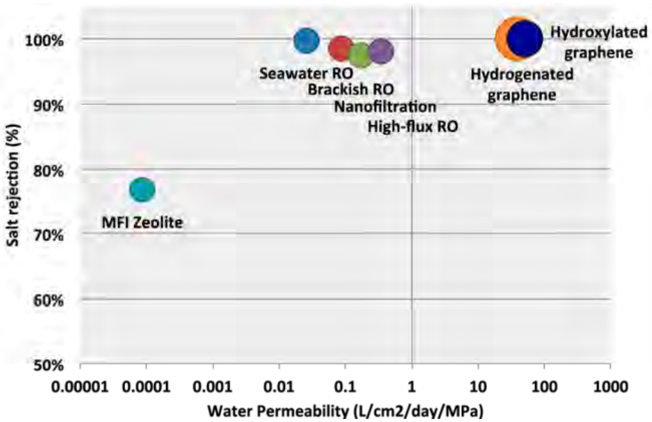
R. R. Nair, et. al., Science, 2012, 335, 442

Graphene sheets for desalination of sea water and arsenic removal

Desalination of sea water

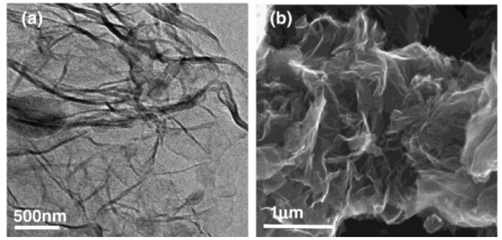


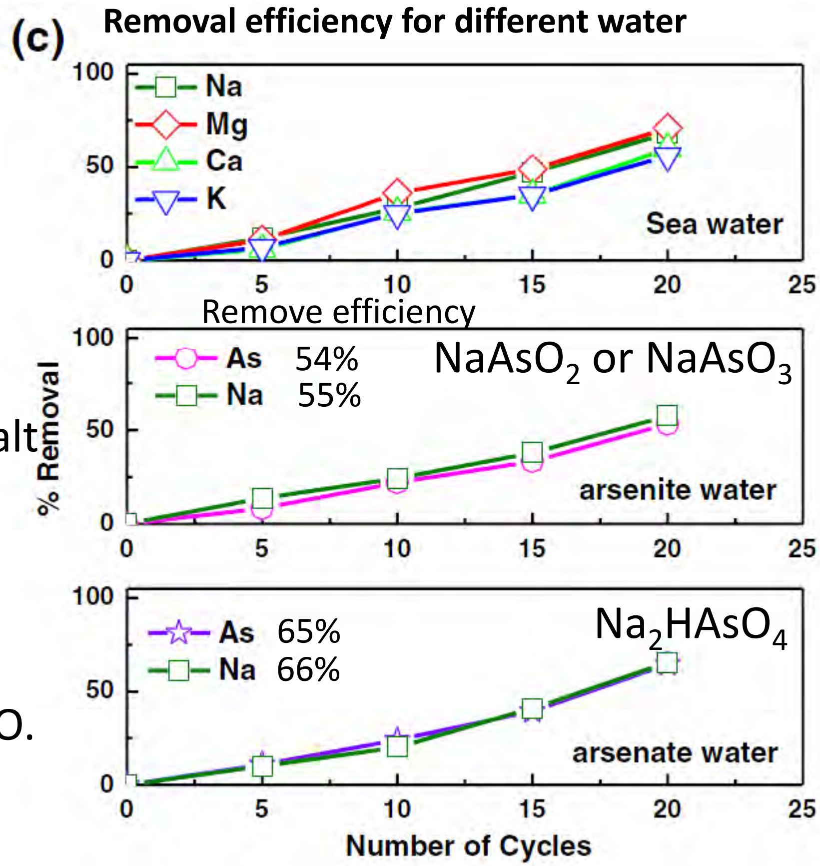
Pure H_2O H_2O+ Na^+ + Cl^-



The graphene nanopores reject salt ions with a water permeability 2–3 orders of magnitude higher than commercial RO.

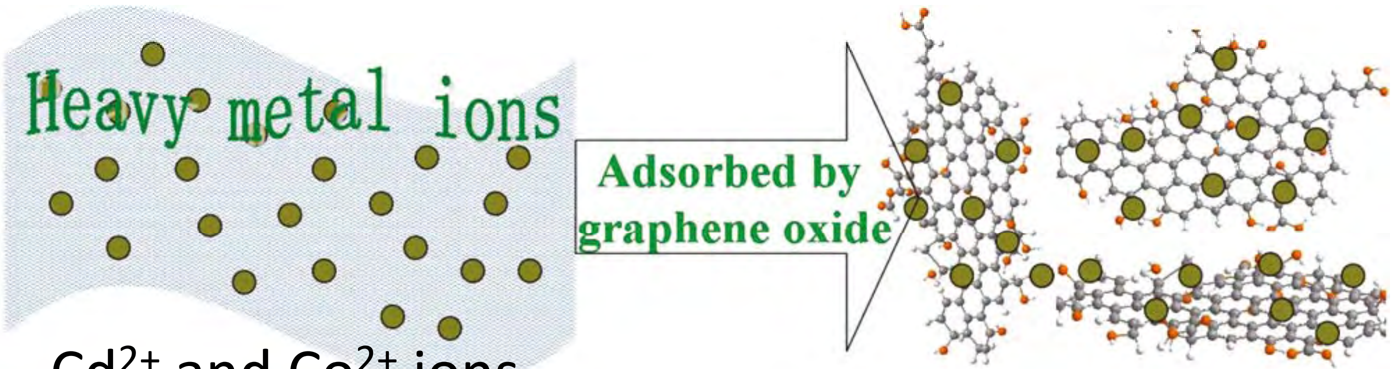
TEM SEM



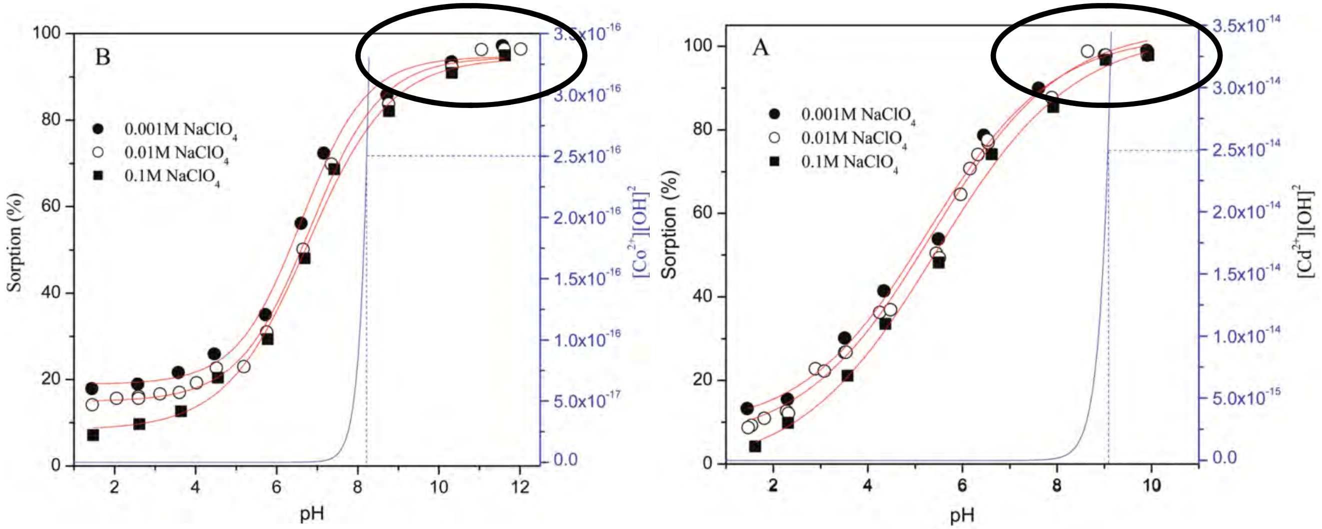


Cohen-Tanugi D. et. al., Nano Lett. 2012, 12, 3602−3608
Ashish Kumar Mishra,et. al., Desalination 282 (2011) 39–45

Few-Layered Graphene Oxide Nanosheets As Superior Sorbents for Heavy Metal Ion Pollution Management



Cd^{2+} and Co^{2+} ions



Most Cd^{2+} and Co^{2+} is adsorbed on GO nanosheets at pH > 9.

Zhao, G., et. al. Environ. Sci. Technol. 2011, 45, 10454–10462