MANCHESTER 1824

The University of Manchester

Graphene: Materials in the Flatland

K.S. Novoselov

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Graphene: Materials in the Flatland

est imaginable material

strongest material ever measured (theoretical limit)

stiffest known material (stiffer than diamond)

most stretchable crystal (up to 20% elastically)

record thermal conductivity (outperforming diamond)

highest current density at room T (million times of those in copper)

highest intrinsic mobility (100 times more than in Si)

conducts electricity in the limit of no electrons

lightest charge carriers (zero rest mass)

longest mean free path at room T (micron range)

K.S. Novoselov

Three Key-Points

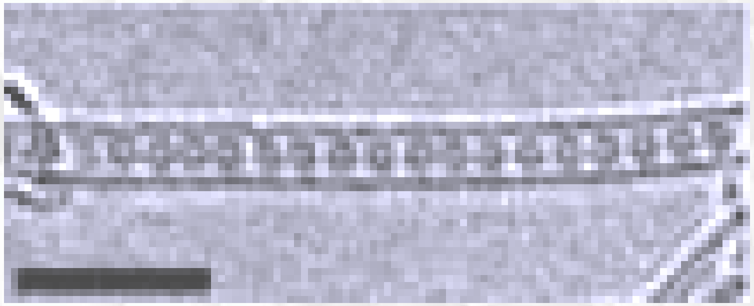
The First Two-Dimensional Crystal

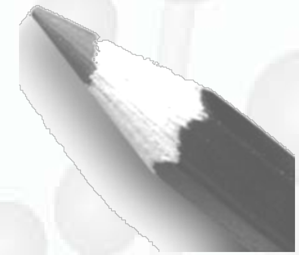
Unusual Electronic Properties

Promising For Applications

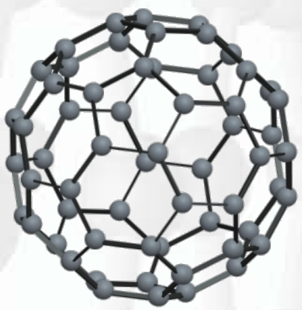
The First Two-Dimensional Crystal

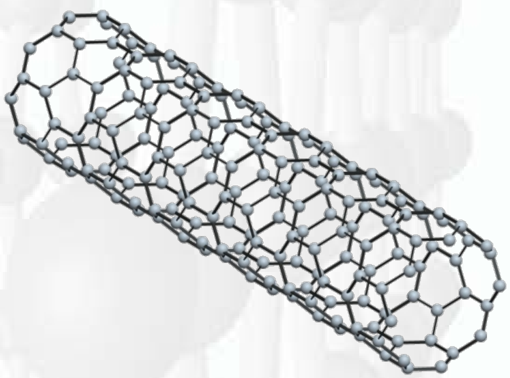
Two-Dimensional Form of Carbon

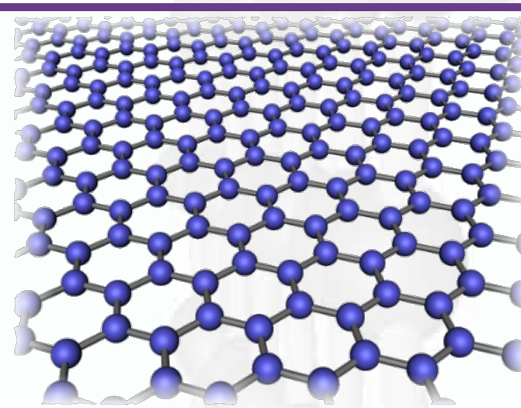


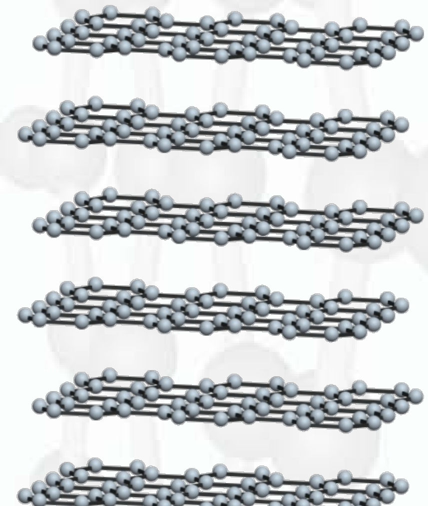


0d | 1d | 2d | 3d









"Buckyball"

R. F. Curl
H.W. Kroto
R. E Smalley 1985
Nobel prize 1996

Carbon Nanotube

Multi-wall 1991
Single-wall 1993

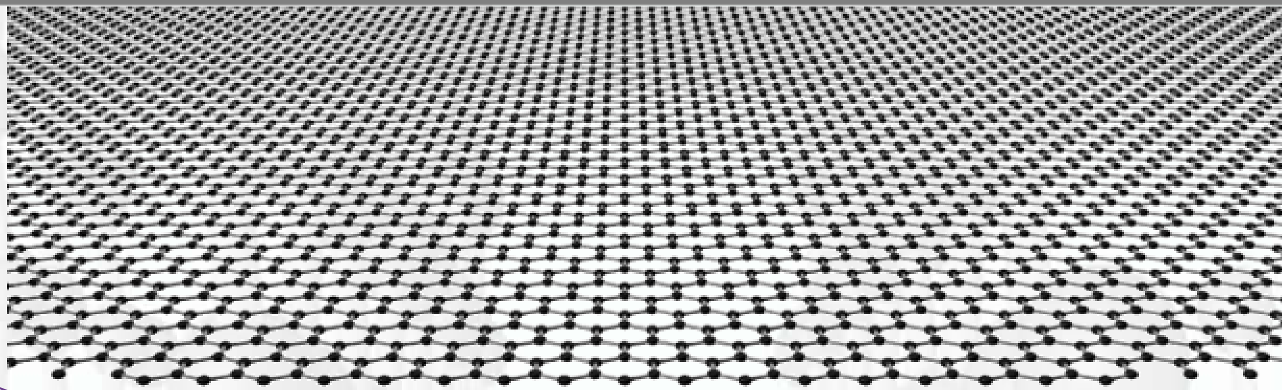
Graphene

Graphite

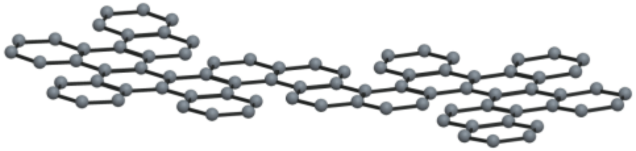
1564
Borrowdale

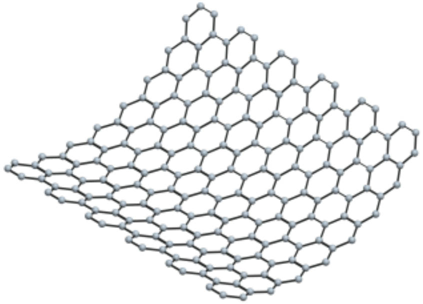
Carbon Allotropes

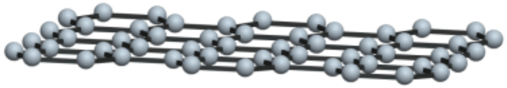
2d
Graphene



0d **1d** **3d**

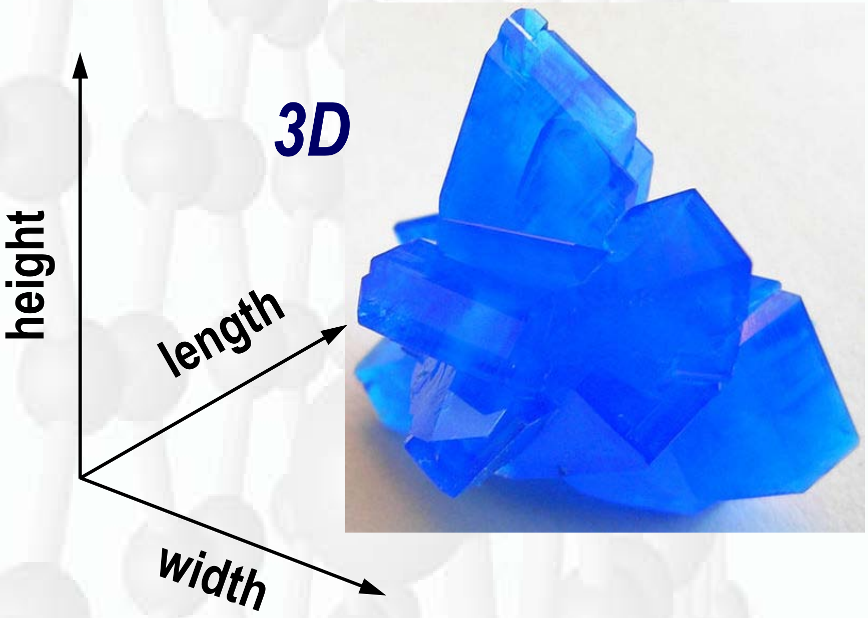


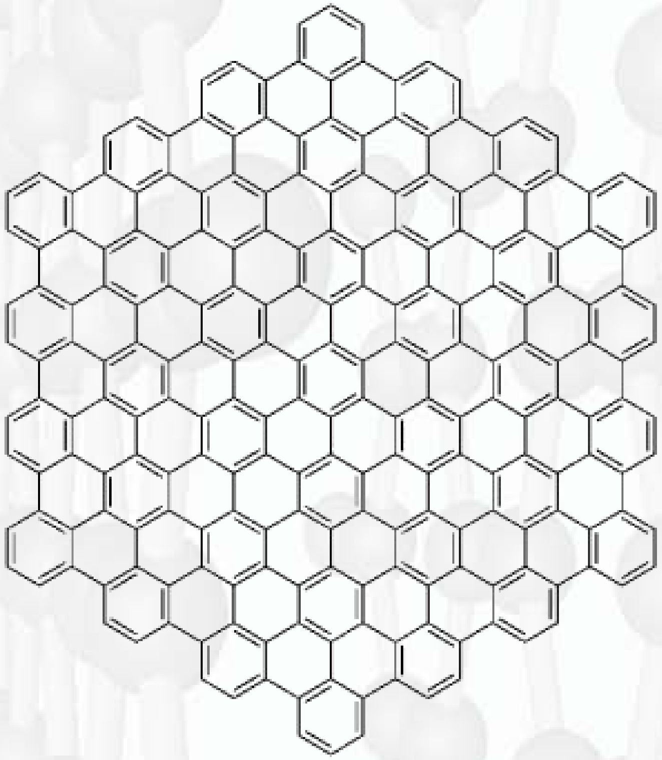




"Buckyball" Carbon Nanotube Graphite

All Natural Materials Are 3D



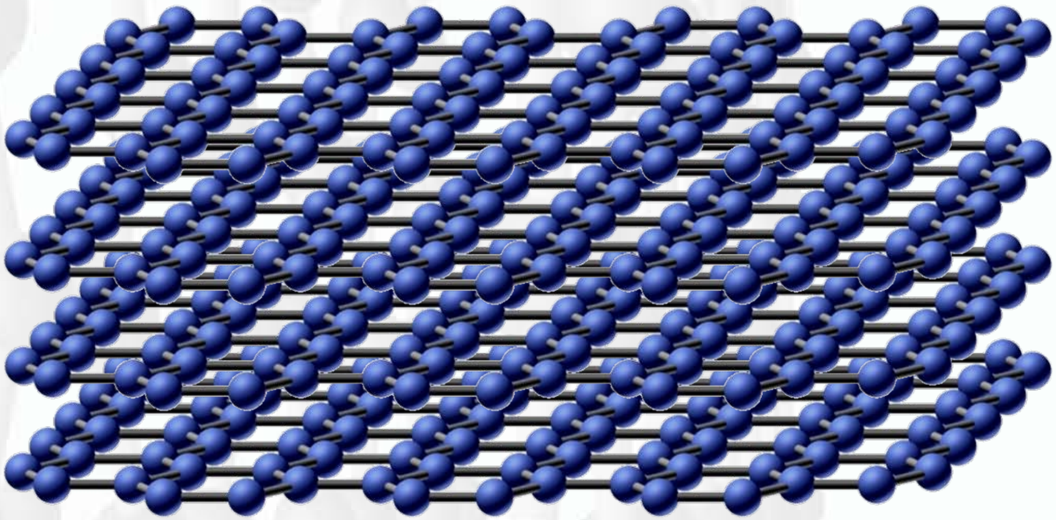


largest known
flat hydrocarbon:
222 atoms or 37 benzene rings
(K. Müllen 2002)

Can We Cheat Nature?

Slice down to one atomic plane

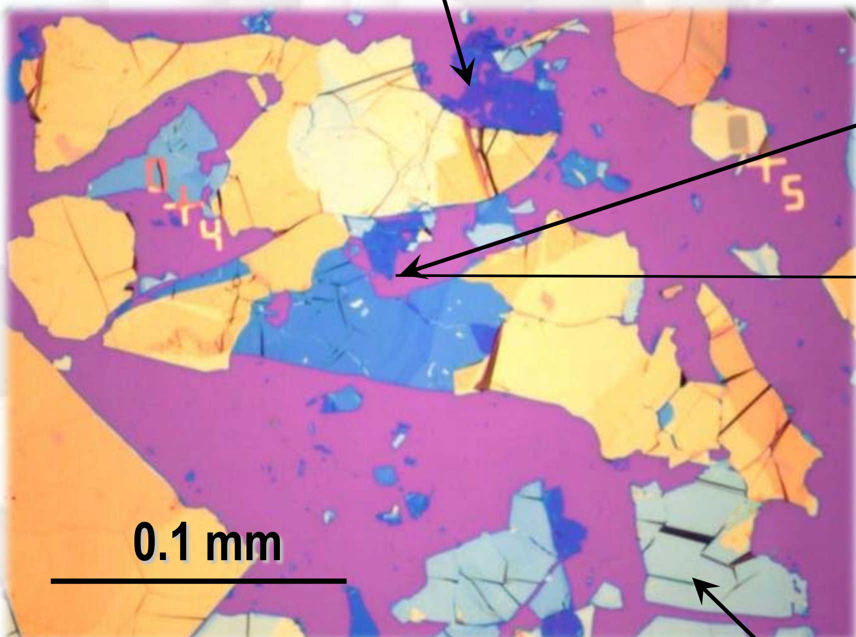
Strongly layered material

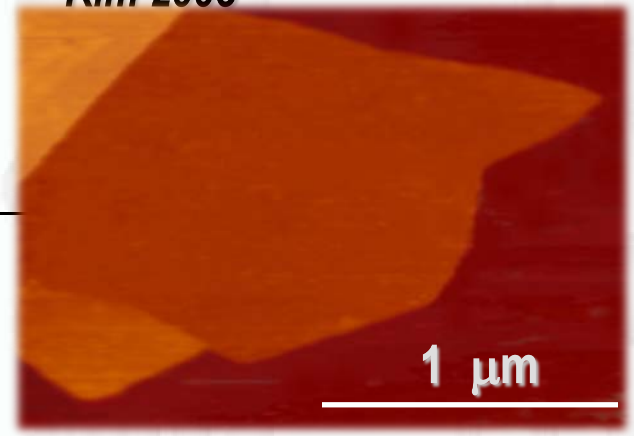


Into The Pencil Trace

1-5 layers Manchester 2004

10 to 30 layers
Kim 2005



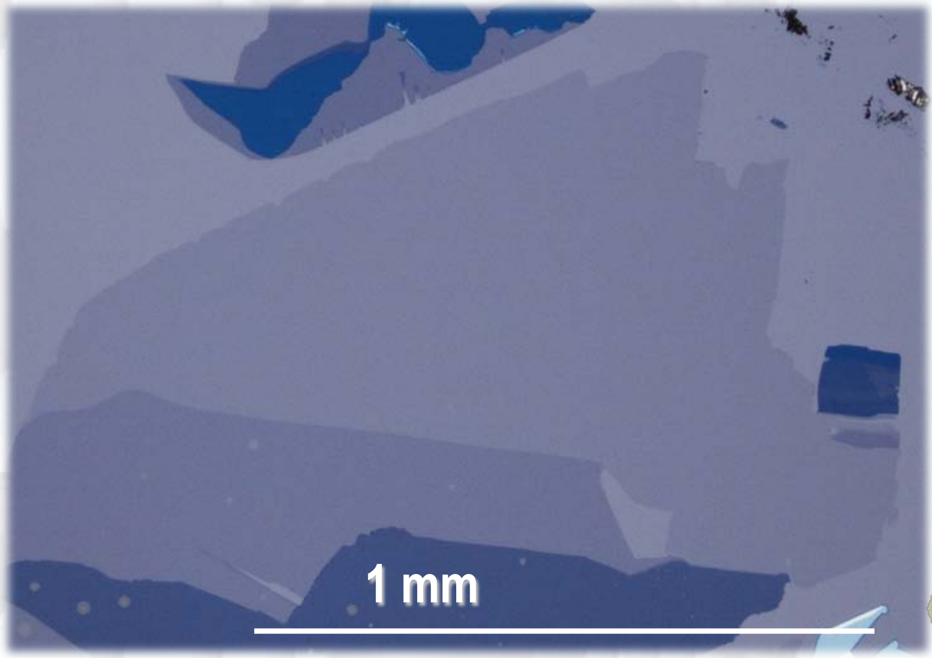


first 2D material demonstrated
- Manchester, Science ‘04

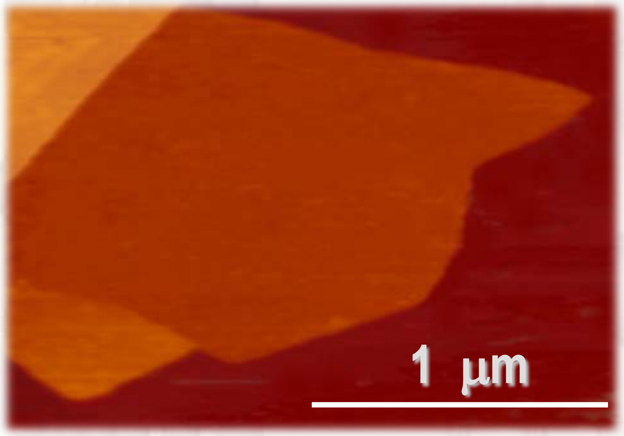
graphite trace on oxidized Si wafer

~100 layers
Kurtz 1991
Dujardin 1997
Ohashi 1997
Ruoff 1999

Into The Pencil Trace



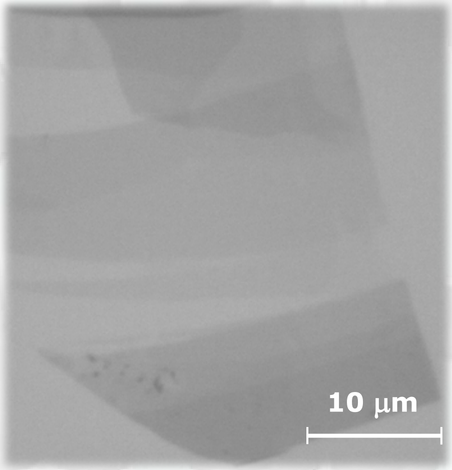
graphite trace
on oxidized Si wafer

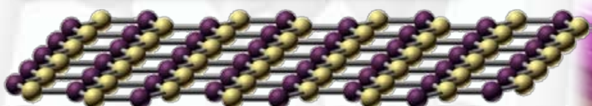


first 2D material demonstrated
- Manchester, Science '04

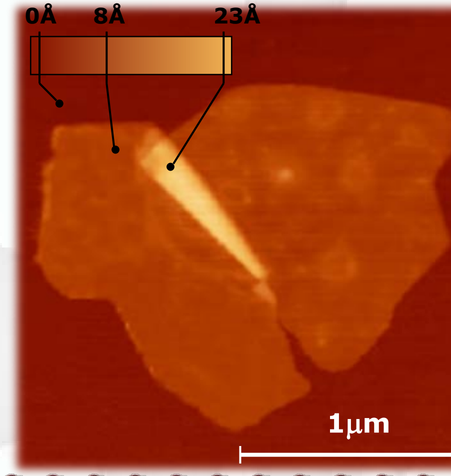
Other 2D Crystals

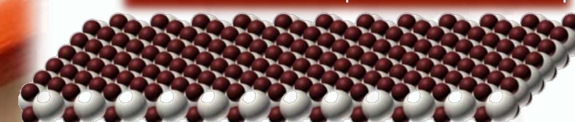
2D boron nitride in optics





2D $NbSe_2$ in AFM

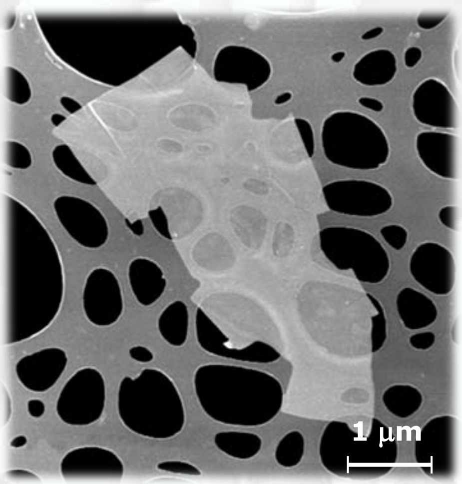




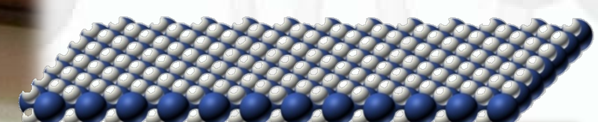
From 3D systems

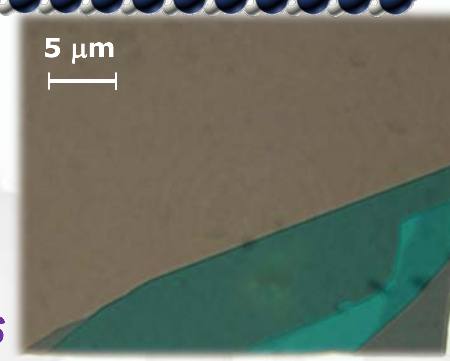
Novoselov et al PNAS (2005)

High Quality
Different From 3D Precursor



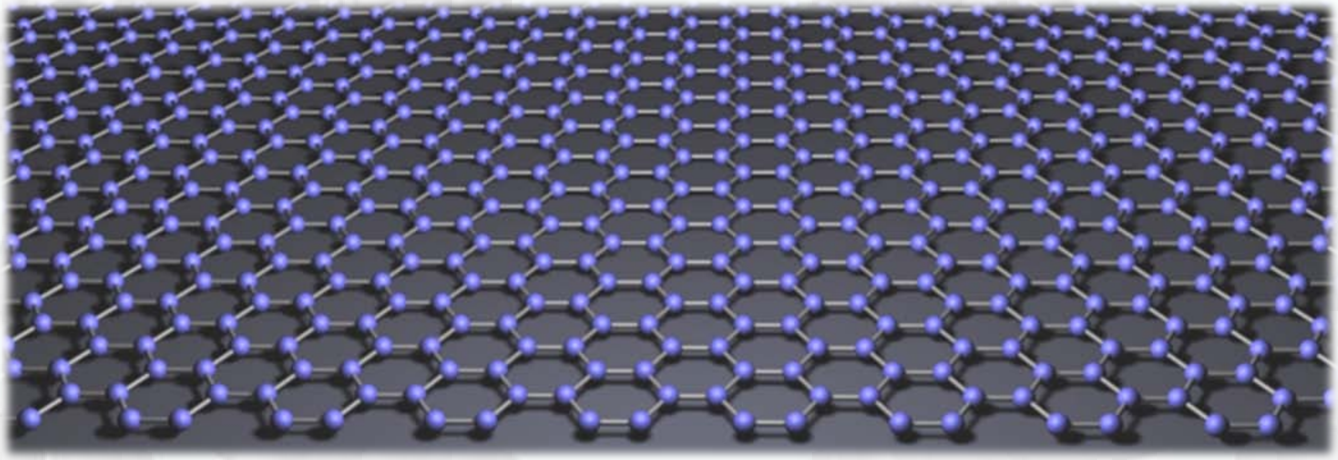
2D $Bi_2Sr_2CaCu_2O_x$ in SEM



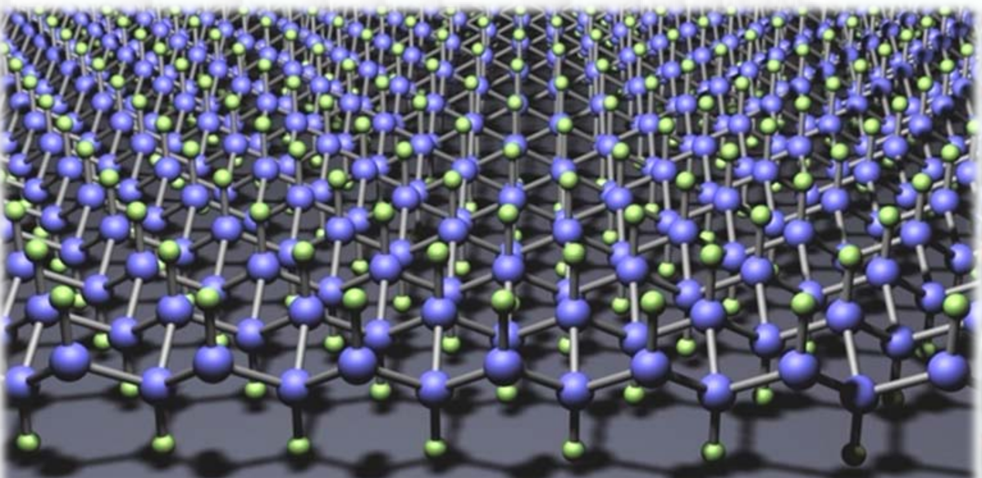


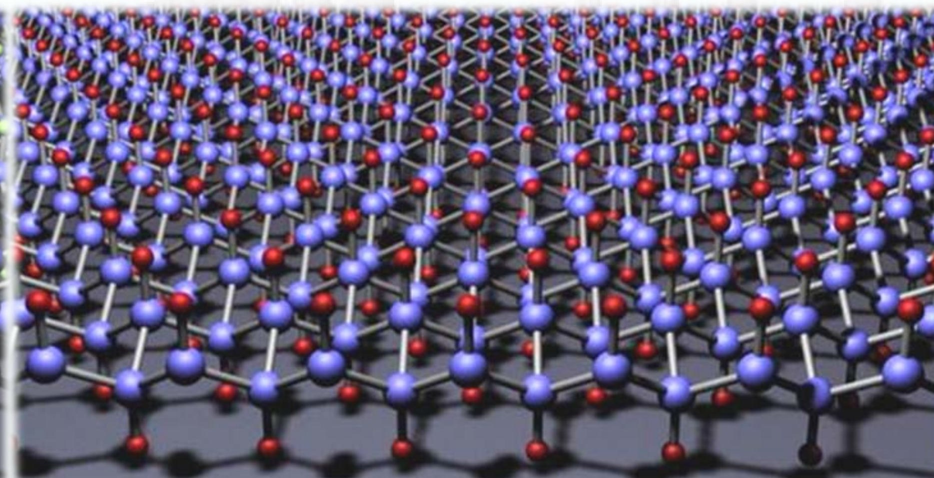
2D MoS_2 in optics

Other 2D Crystals



$C_\infty + \infty F \Rightarrow (CF)_\infty$ **By Chemical Reaction** $C_\infty + \infty H \Rightarrow (CH)_\infty$





FLUOROGRAPHENE (graFane)
Manchester Small '10

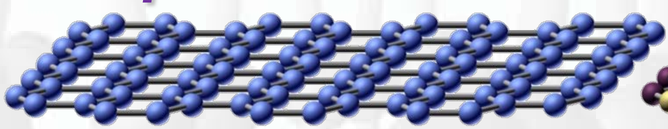
graphane
Manchester Science '09

New Class of Crystalline Materials

2-DIMENSIONAL ATOMIC CRYSTALS

Studied (???):

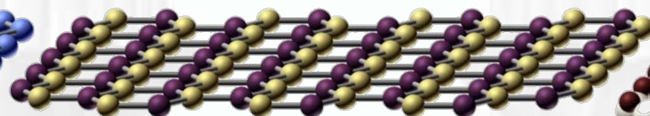
Graphene



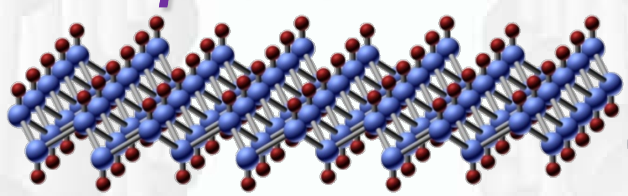
Large Variety of Material Properties

Lightly Touched:

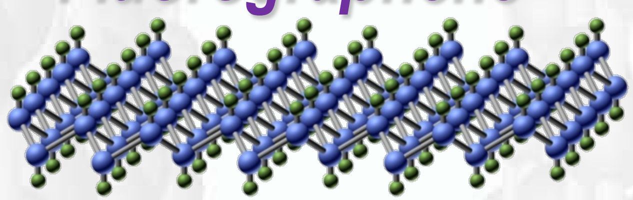
Boron-Nitride



Graphane

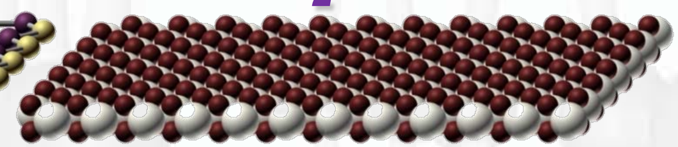


Fluorographene

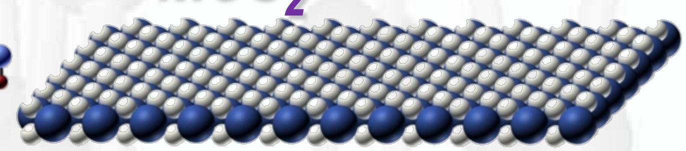


Unexplored:

$NbSe_2$



MoS_2



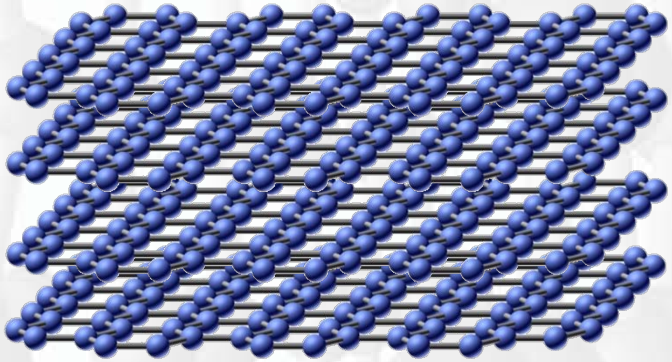
MgB_2

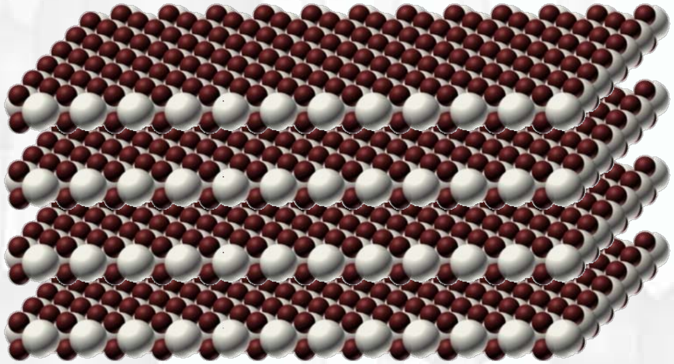
BiSCCO

...

A Dream: Back From The FLATLAND

Materials on Demand

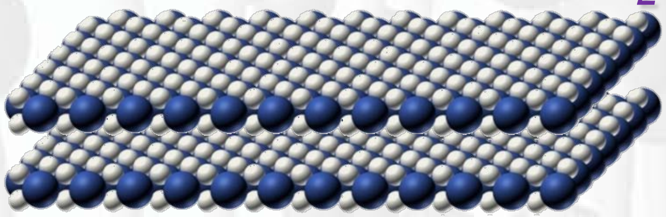




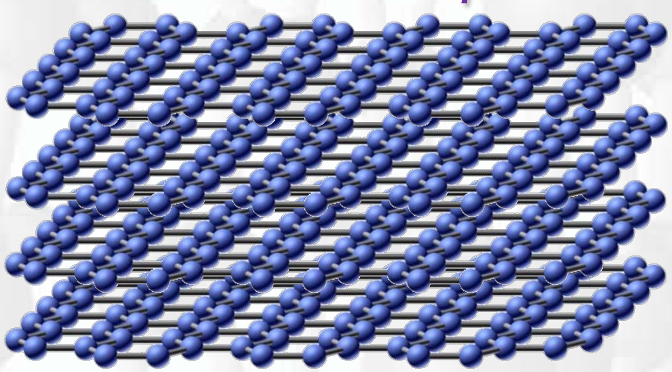
What kind of properties would this material possess?

2D-Crystals-Based Heterostructures

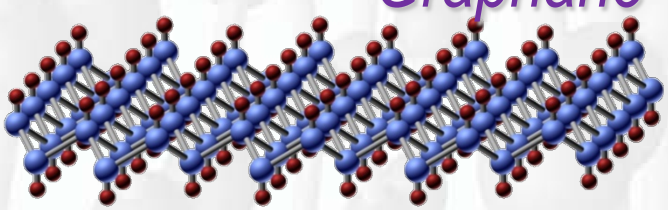
MoS_2

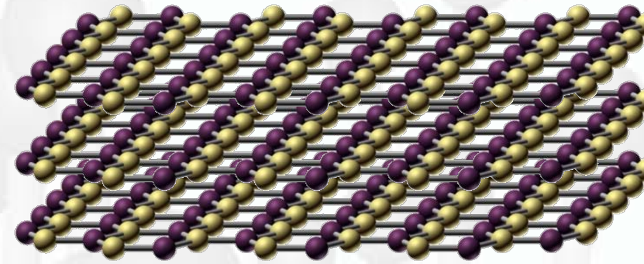


Graphene

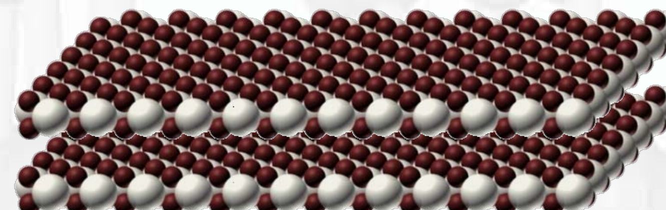


Graphane

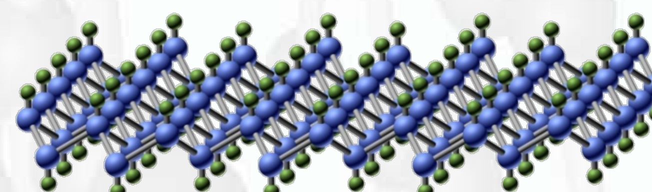




Boron-Nitride



$NbSe_2$



GraFane

2D-Crystals-Based Heterostructures

Graphene

ultimately thin

linear gapless spectrum

chemically active
(new materials:
graphane, flurographene)

New Material: Bilayer Graphene

two layers – can slide

parabolic gapless spectrum
(chiral massive particles)
GAP CAN BE OPENED

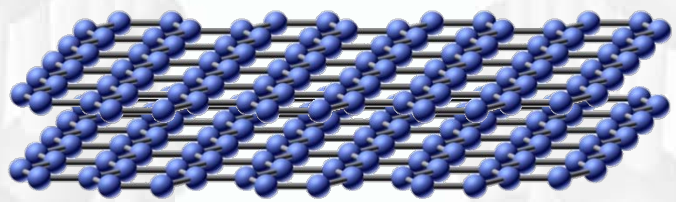
chemically less active

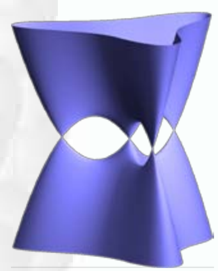
Graphite

cleaves easily

semimetal

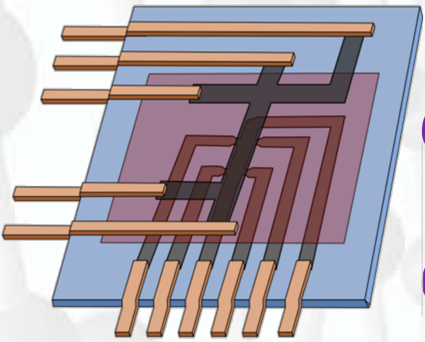
inert

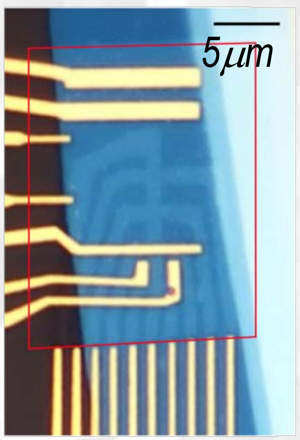


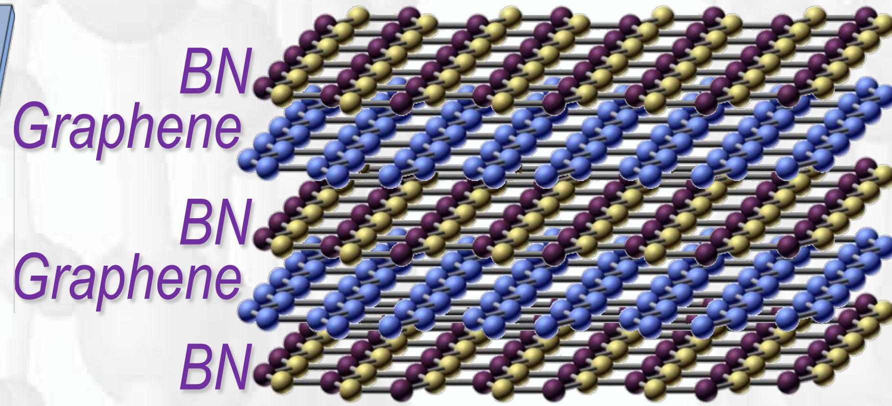


Manchester, Nature Phys. (2007)
Zhang et al, Nature (2009)
Kuzmenko et al, PRB (2009)
Young et al arXiv:1004.5556v2
Oostinga et al, Nature Mat (2007)

2D-Crystals-Based Heterostructures

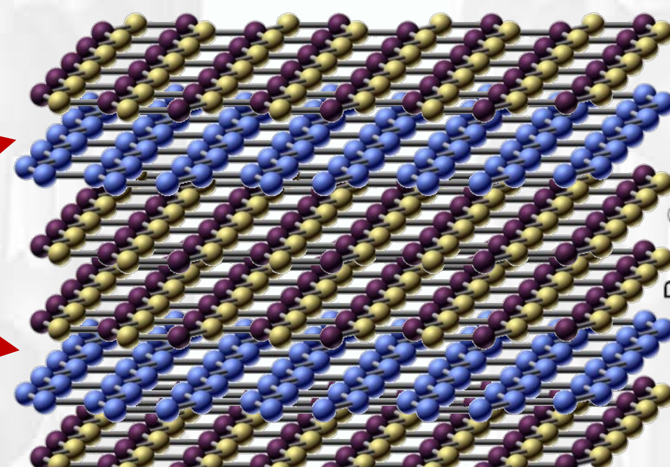


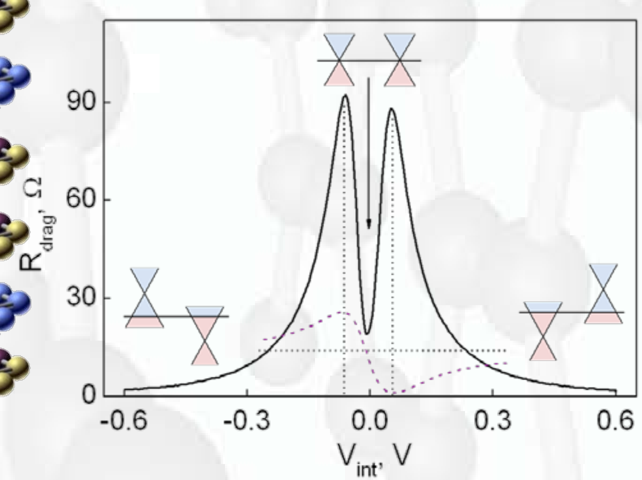




Strong Coupling
(tunnelling regime)

Weak
Coupling
(Coulomb interaction)





Coulomb Drag

Three Key-Points

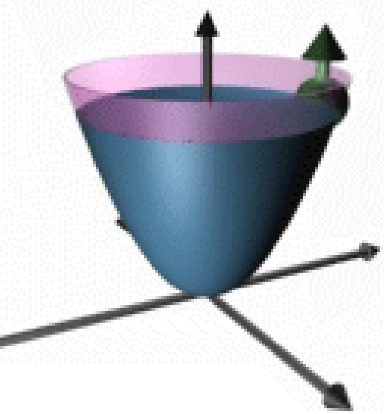
Unusual Electronic Properties

New Types of Quasiparticles

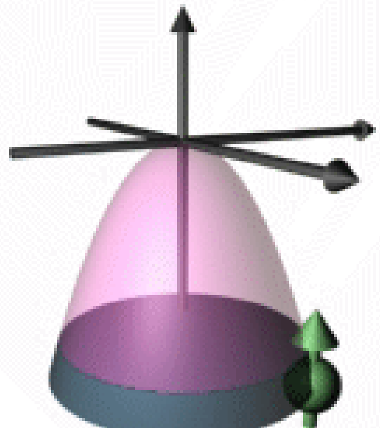
"Schrödinger fermions"

$$\hat{H} = \hat{p}^2 / 2m^*$$

Electron metal



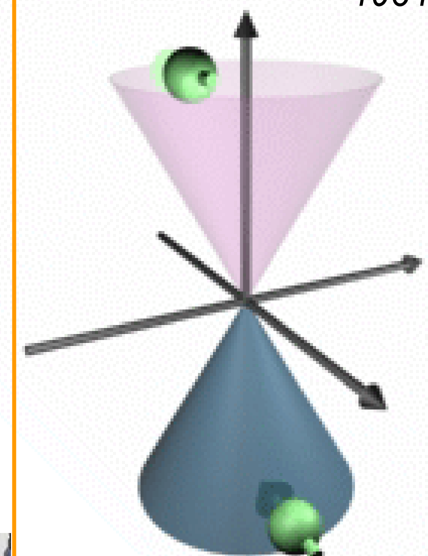
Hole metal



massless Dirac fermions

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

Semenoff 1984



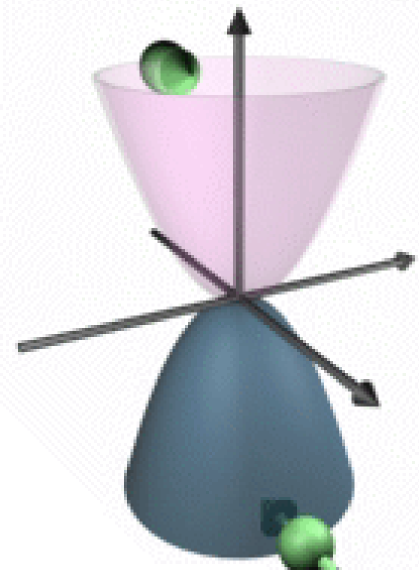
monolayer graphene

neutron stars & accelerators

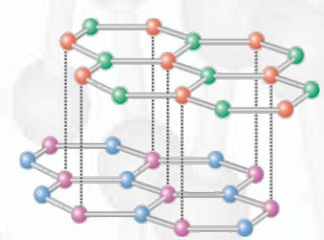
massive chiral fermions

$$\hat{H} = \vec{\sigma} \cdot \hat{p}^2 / 2m^*$$

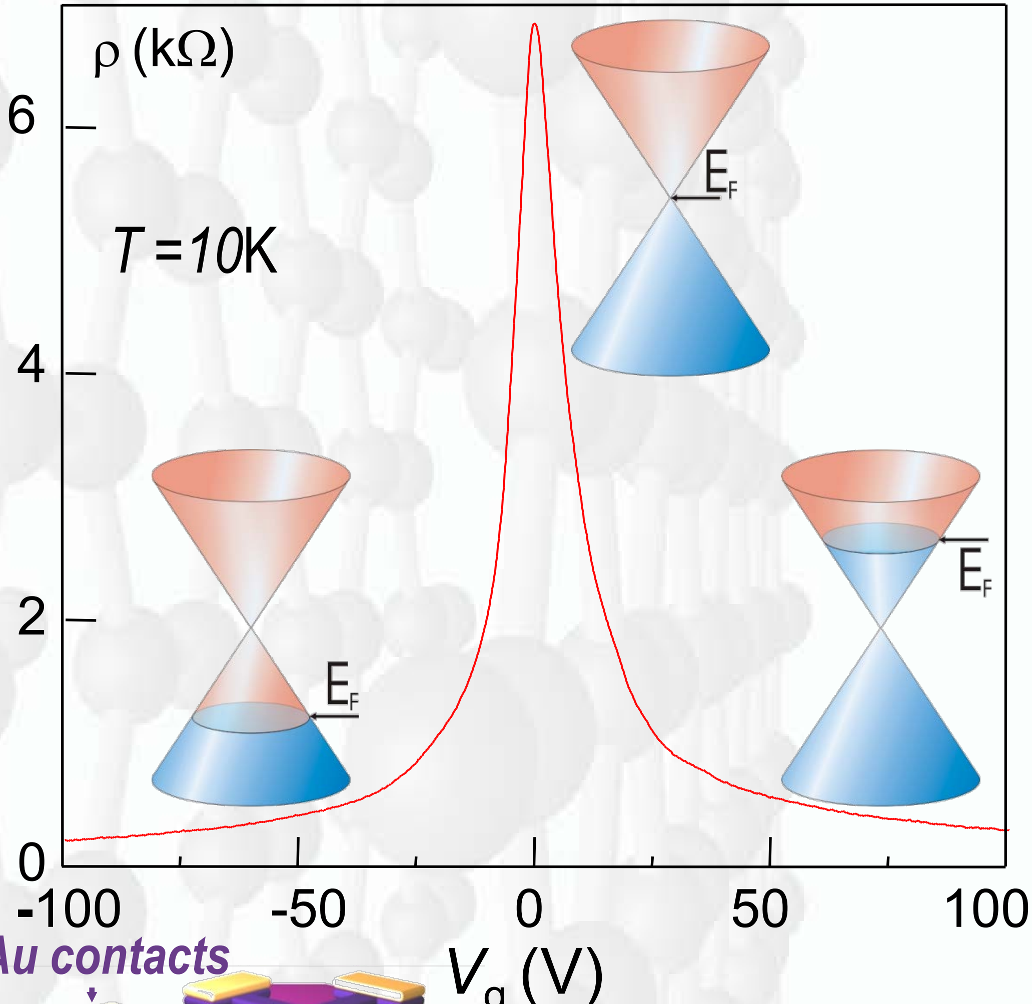
Falko 2006

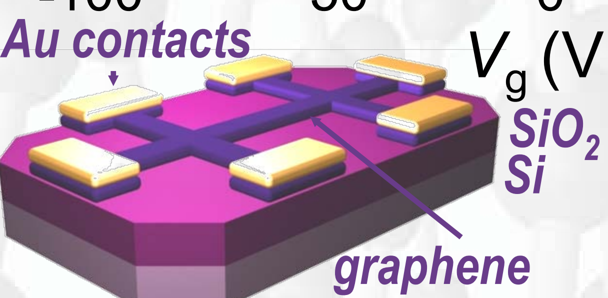


bilayer graphene



Graphene Field Effect Transistors



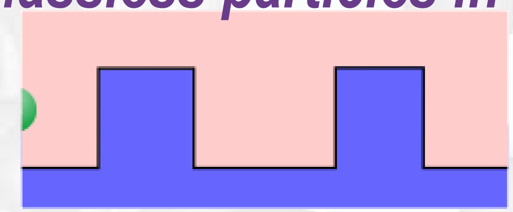


carrier mobility <u>currently</u>:
up to ~50,000 $cm^2/V{\cdot}s$ at 300K
even when strongly doped

~1,000,000 $cm^2/V{\cdot}s$ at 4K
(Andrei, Kim & Manchester group)

<u>intrinsic (phonon-limited)</u>:
>200,000 $cm^2/V{\cdot}s$ at 300K
(higher than in any other material)

Massless particles in 2D:

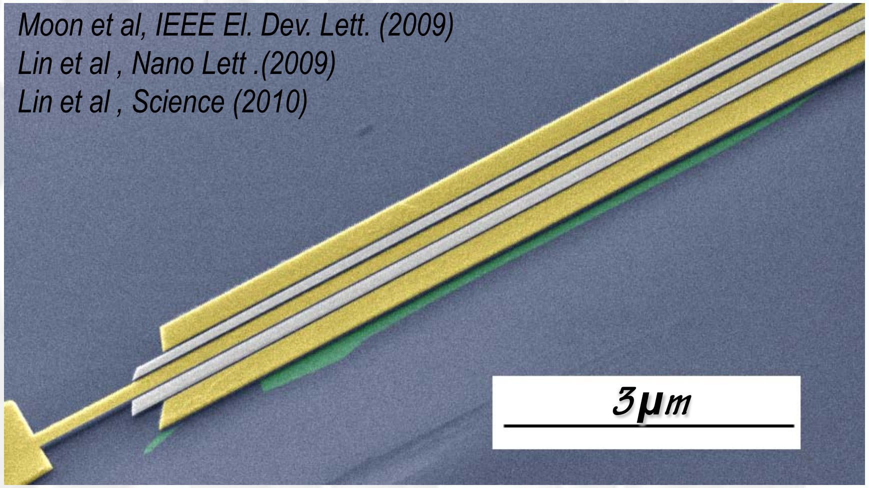


Klein paradox

NEVER LOCALIZED

O. Klein, Z. Phys 53,157 (1929); 41, 407 (1927)
M.I.Katsnelson et al Nature Physics (2006)
Young et al Nature Physics (2009)

Graphene Transistors



ballistic transport between source & drain: THz range

ultra high-F analogue transistors:

HEMT design;

"standard" mobilities;

on-off ratio: ~100

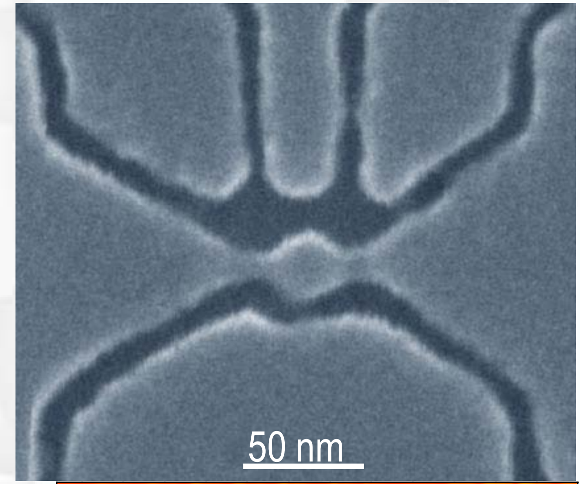
Manchester, Science '04

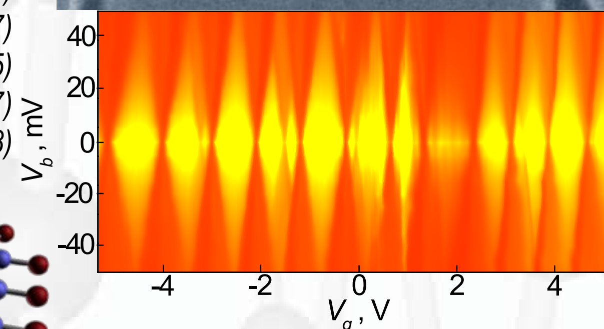
100GHz @ 240nm channel – better than Si

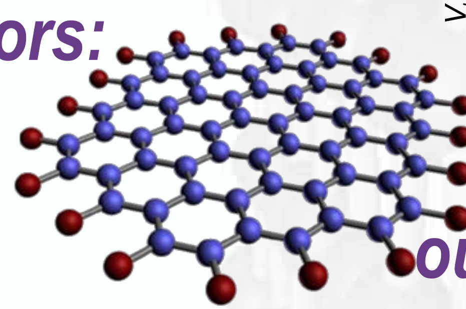
even with very modest mobility of 1.500cm^2/V·s

Graphene Quantum Dots and Single Electron Transistors

Ponomarenko et al Science (2008)
Ozyilmaz, et al. APL (2007)
Geim & Novoselov Nature Mat (2007)
Bunch et al Nano Lett (2005)
Miao et al Science (2007)
Stampfer et al APL (2008)







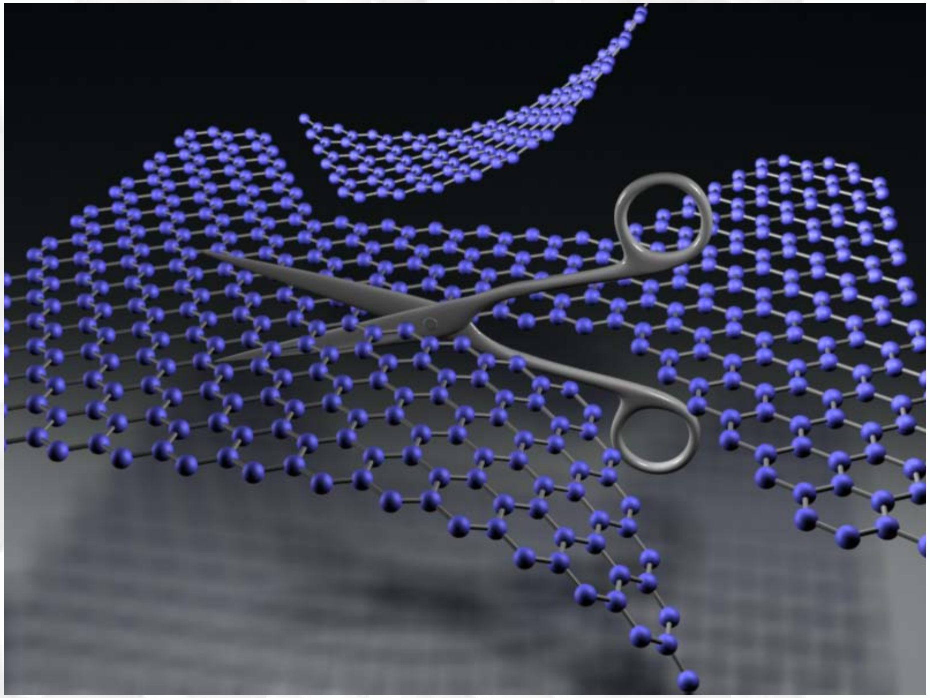
our smallest QD~1nm

Top-Down Molecular Electronics

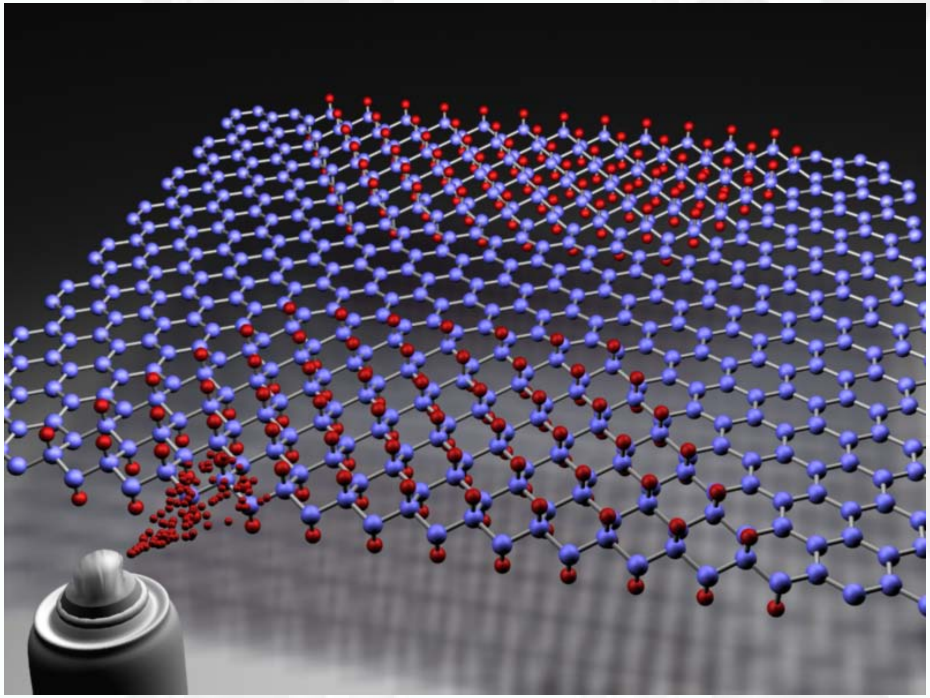
- **Only few benzene rings**
- **Remarkably stable**
- **Sustains large currents**

Paper Cutting vs Paper Painting

Nanoribbons, Quantum Point Contacts, Quantum Dots

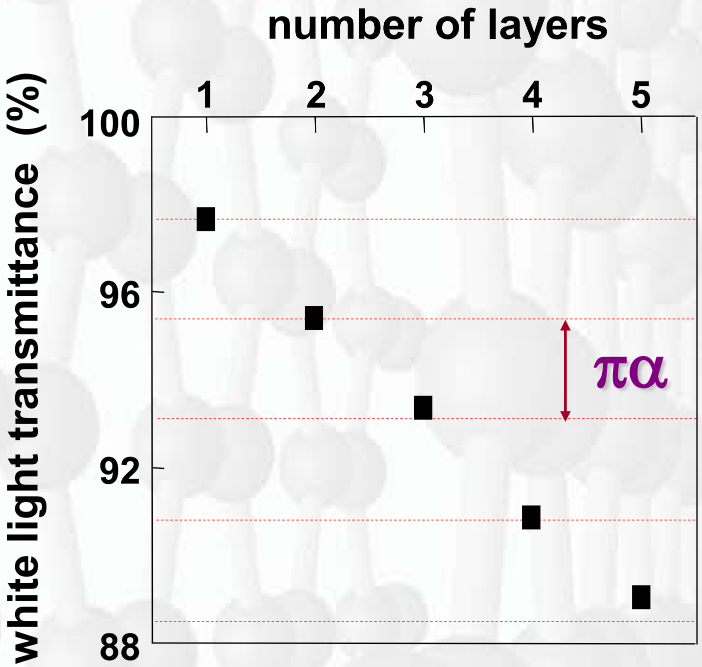


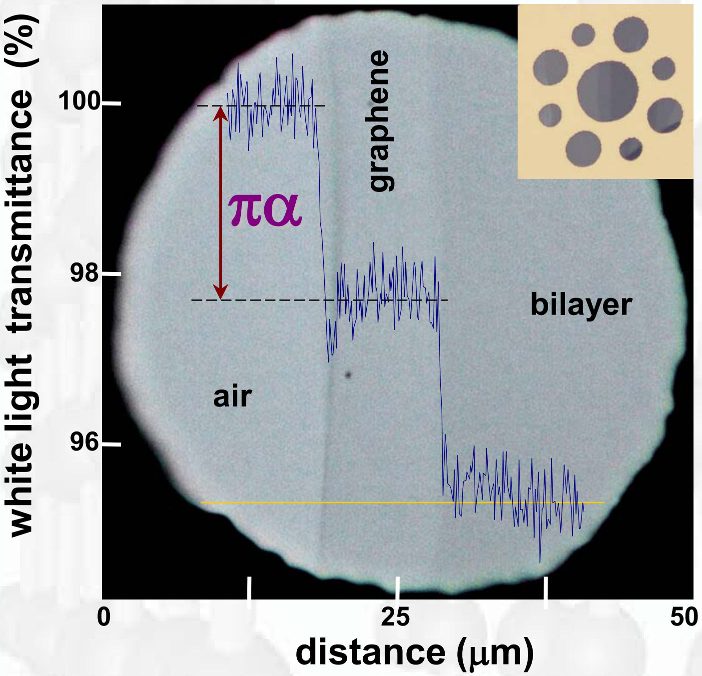
Reactive Plasma Etching



Hydrogenation

Visualisation of Fine Structure Constant





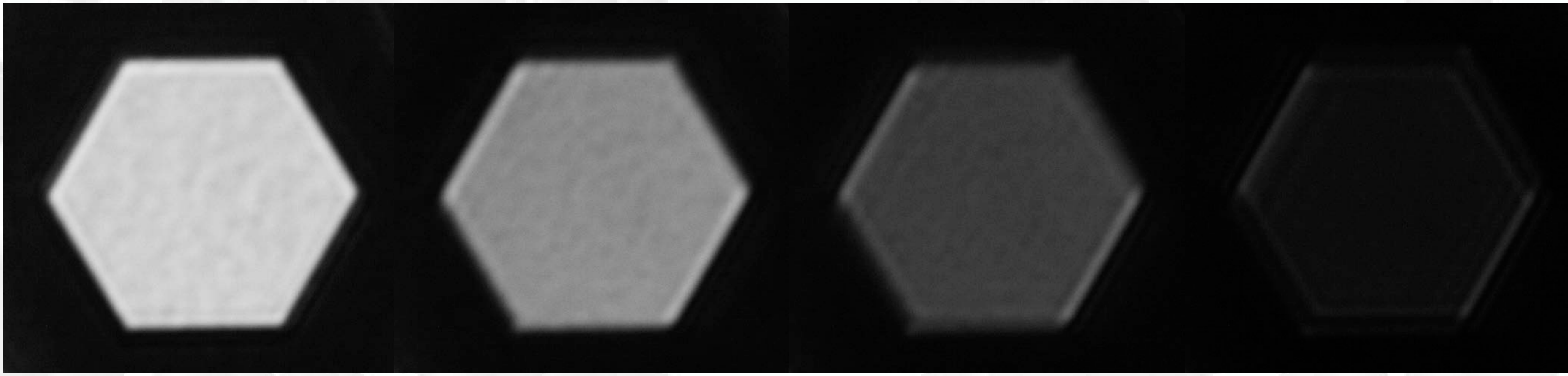
the fine structure constant observed "with a naked eye"
α *= 1/137 (±2%)*

Do it at home

$\pi\alpha$ **= 3.14.. x 1/137**

Manchester, Science '08

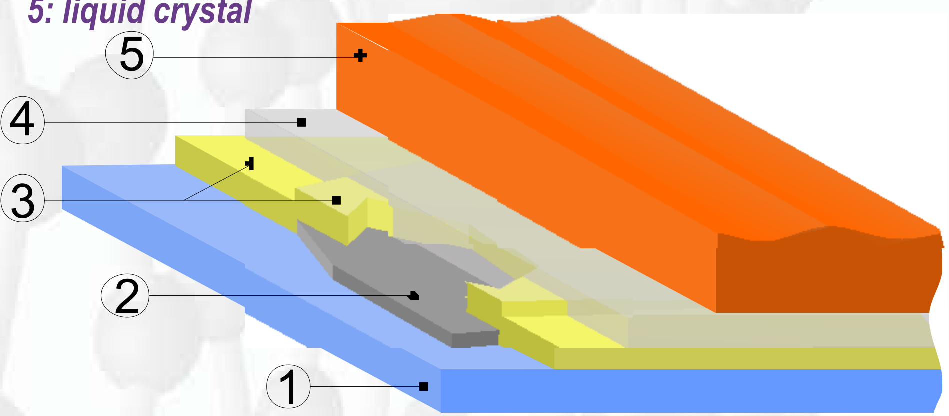
Graphene-based Liquid Crystal Display

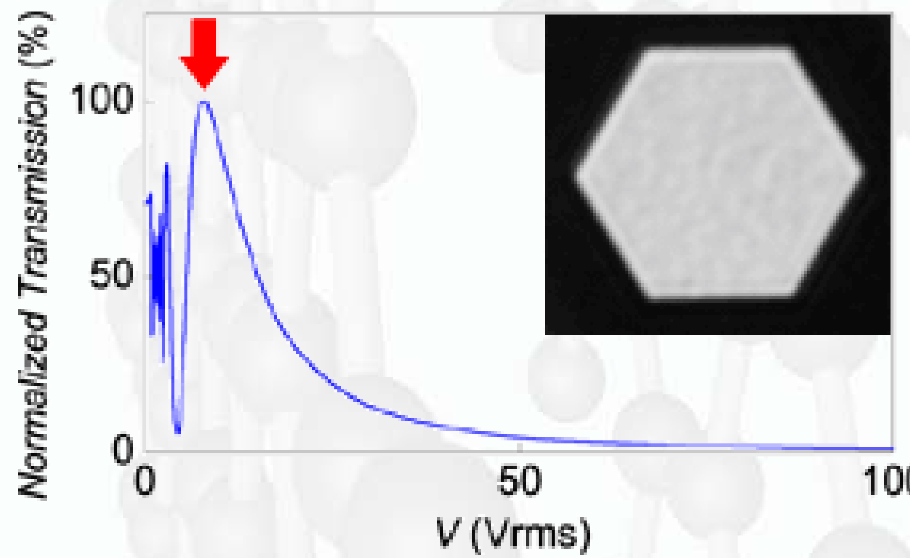


V=0V V=15V V=30V V=100V

High Transparency
High Conductivity
Inert Material

1: glass
2: graphene
3: golden contact
4: aligning layer
5: liquid crystal





Manchester, NanoLetters ‘09

Three Key-Points

Promising For Applications

What Has Graphene Ever Done For Us?

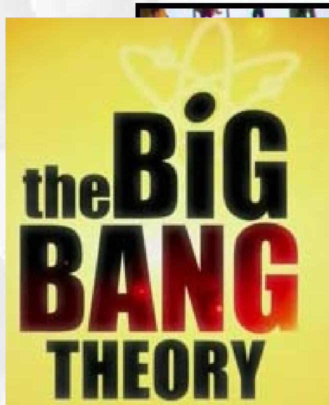
- Create Workplaces

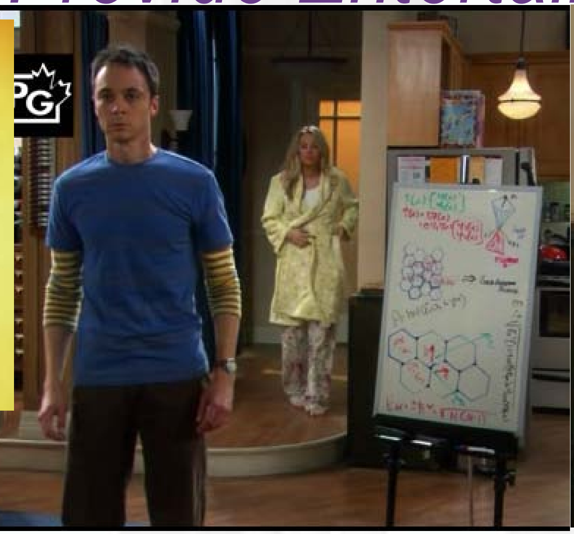
GRAPHENE INDUSTRIES

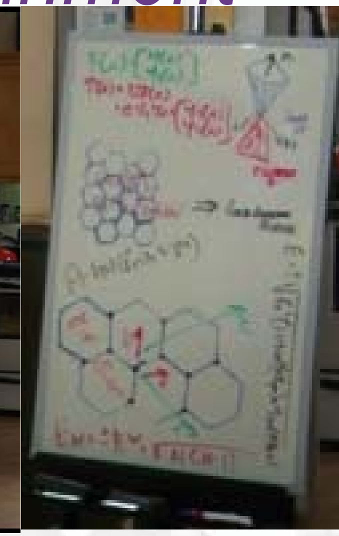
GRAPHENE RESEARCH

GRAPHENE SUPERMARKET

- Provide Entertainment

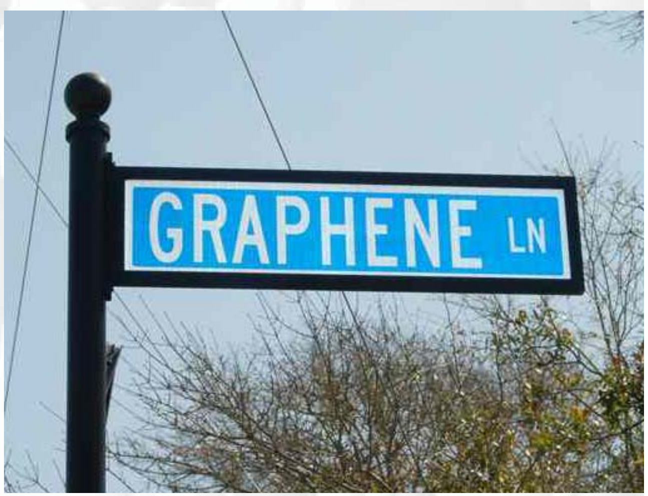


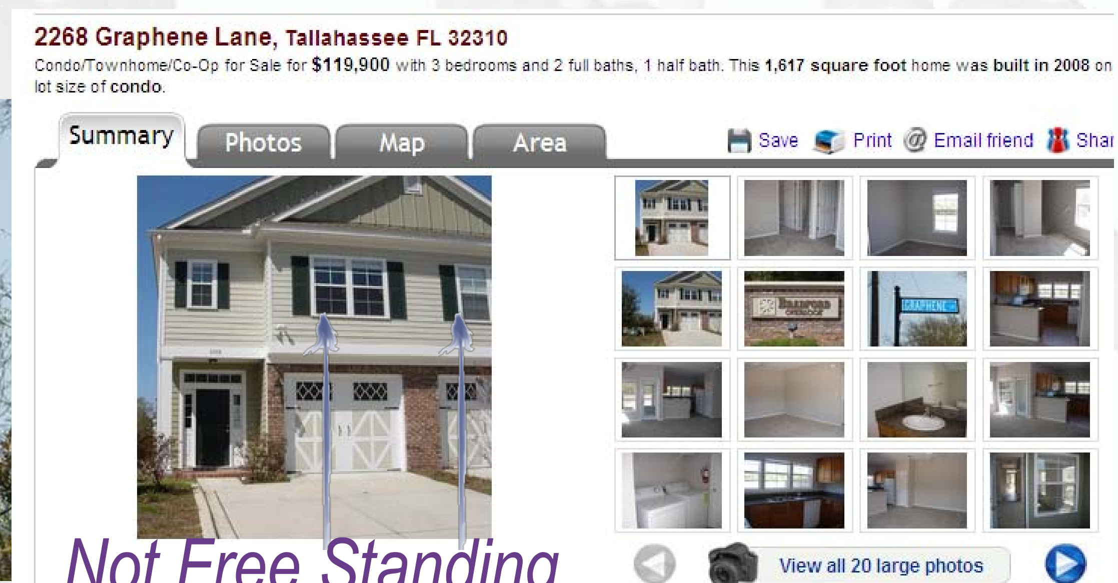




- Give Shelter

Tallahassee, Florida, USA





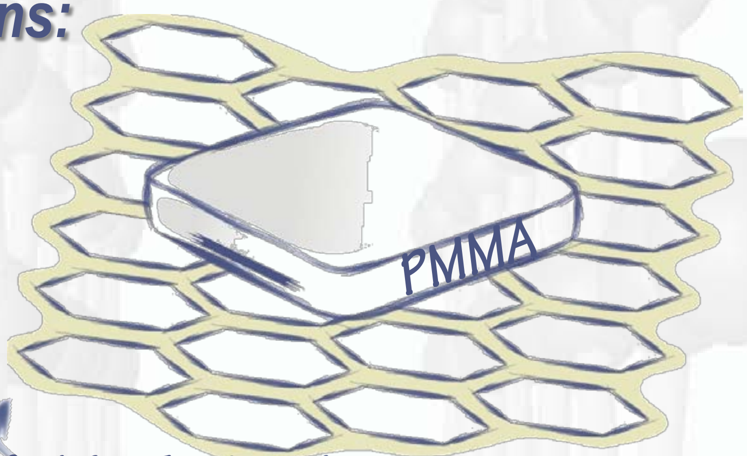
Not Free Standing

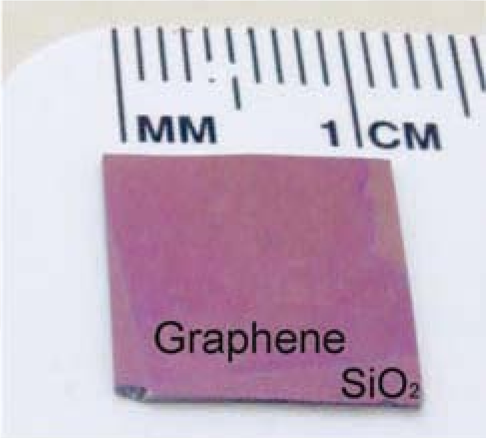
Mass Production of Graphene

CVD growth on Ni, Cu... as part of 3D structure

to quench flexural phonons:

Bommel 1975 (SiC)
McConville 1986 (on Ni)
Land 1992 (on Pt)
Nagashima 1993 (on TiC)
Forbeaux 1998 (SiC)
de Heer 2004 (SiC)
… …





graphene

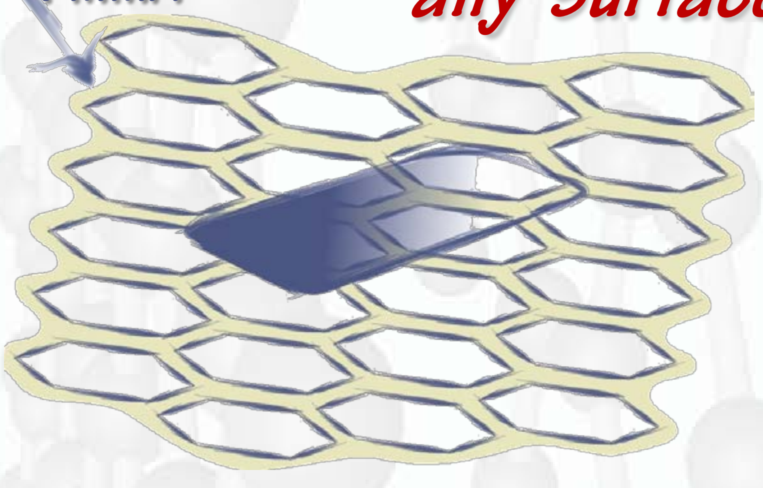
Release graphene by etching Ni

fish by TEM grid

Suggested:
Geim & Novoselov
Nature Mat. (2007)

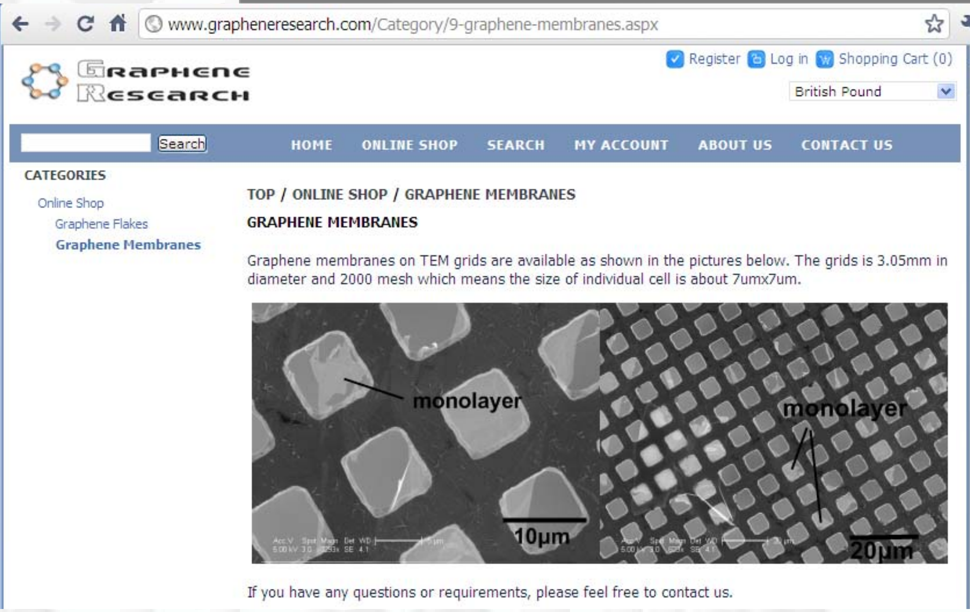
Realised :
MIT (2008)
Yu(2008)
Hong (2009)
Ruoff (2009)

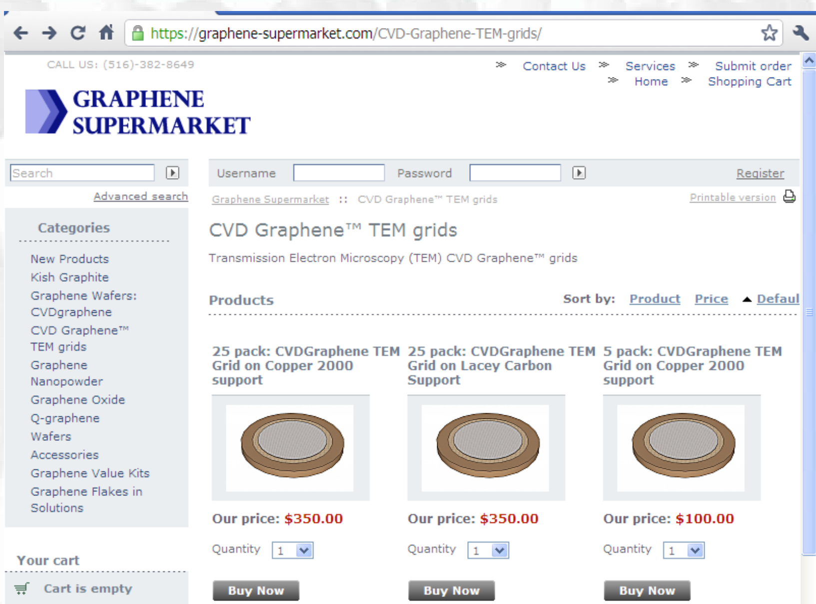
remove PMMA



Direct transfer on any surface

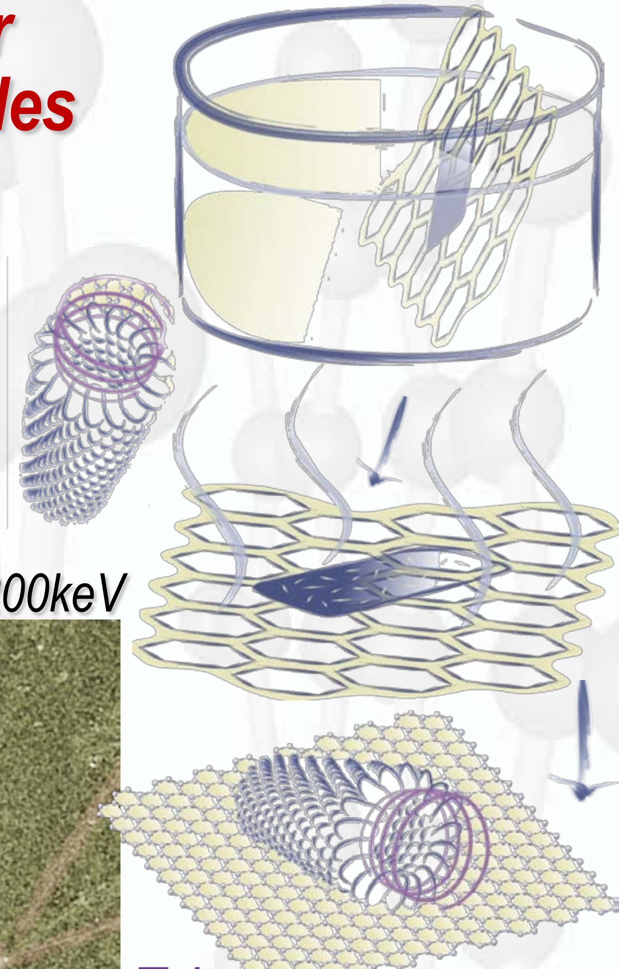
First Graphene Products are Already There





Support for Biomolecules in TEM:

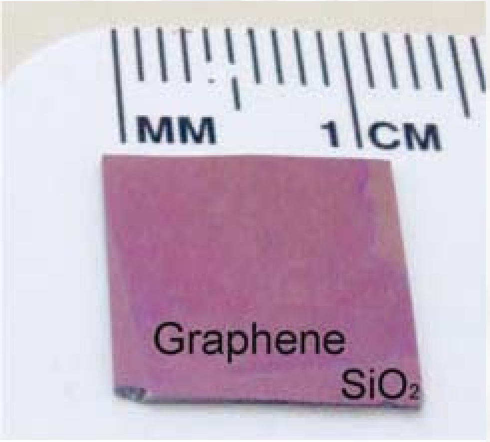
UltraStrong
UltraThin
Crystalline



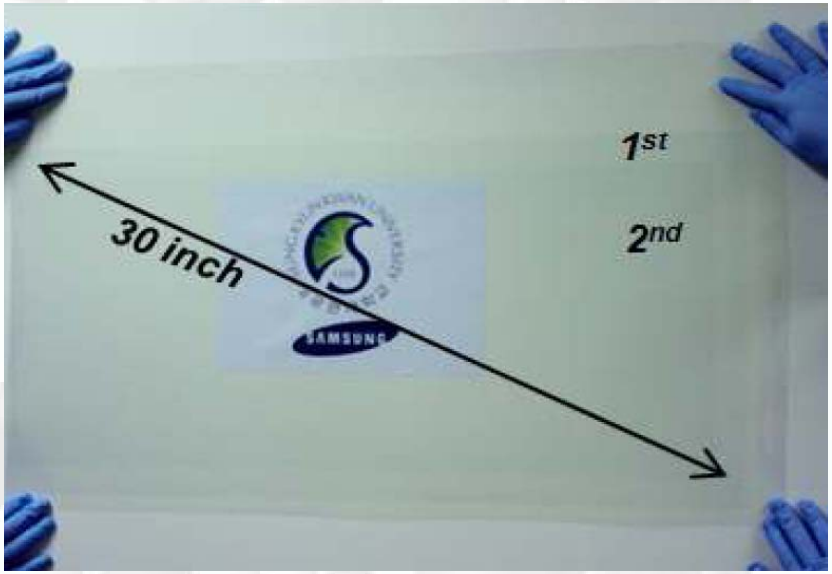
TEM 200keV

Tobacco Mosaic Virus on graphene
Manchester 2010

Mass Production of Graphene

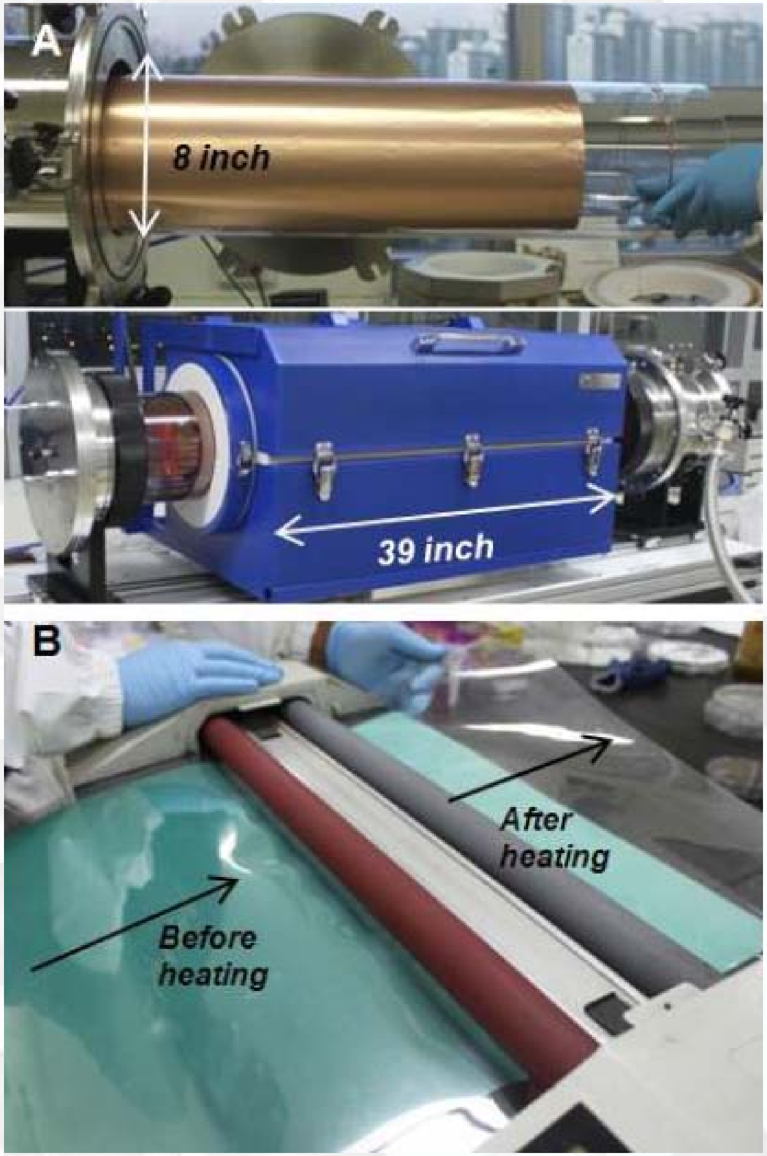


CVD growth & transfer are well developed



ρ ~40Ω/□ transparency ~90%

μ ~5,000 cm²/Vs



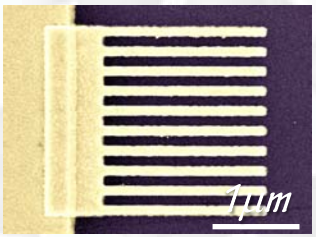
Kim, et al Nature (2009); Li et al Science(2009)

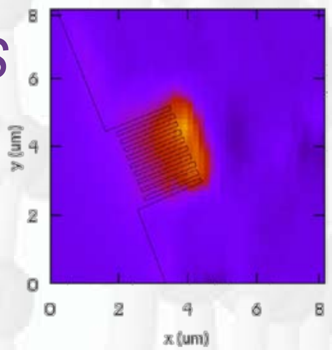
All Major Applications are Realistic

Photovoltaics

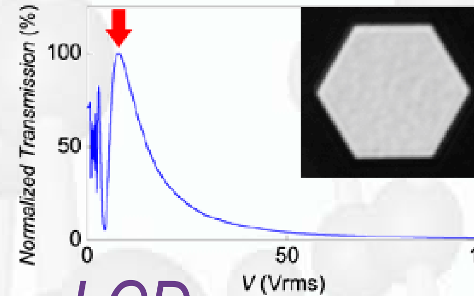
(Samsung roadmap: 2012)

Photodetectors





Touch-screens



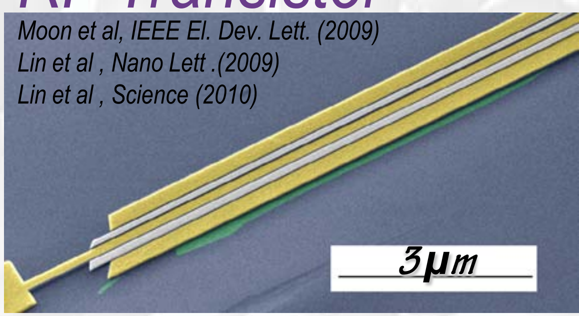
LCD

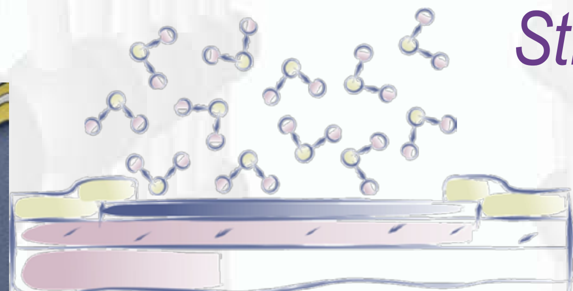
SolarCells

Wang Nano Lett. (2008)

Electronics

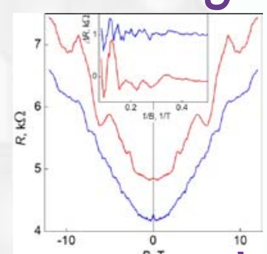
RF Transistor

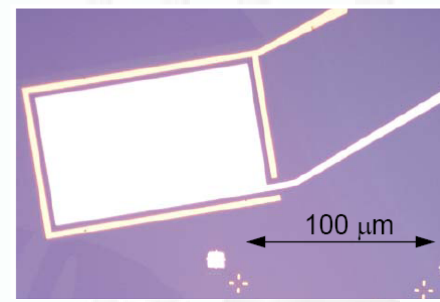




Gas Sensor

Strain Gauge





Variable Capacitor

Composite Materials

Mechanically Strong; Conductive; Optically Active

...

THE ROYAL SOCIETY
erc EPSRC

Big Thanks!!!

A. Geim

Irina GRIGORIEVA
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AND THE REST OF THE FUNTASTIC COMMUNITY