

Graphene: Materials in the Flatland

strongest imaginable material

strongest material ever measured (theoretical limit)

stiffest known material (stiffer than diamond)

most stretchable crystal (up to 20% elastically)

Graphene:

record thermal conductivity (outperforming diamond)

Materials in the Flatland

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)

K.S. Novoselov

longest mean free path at room T (micron range)

Three Key-Points

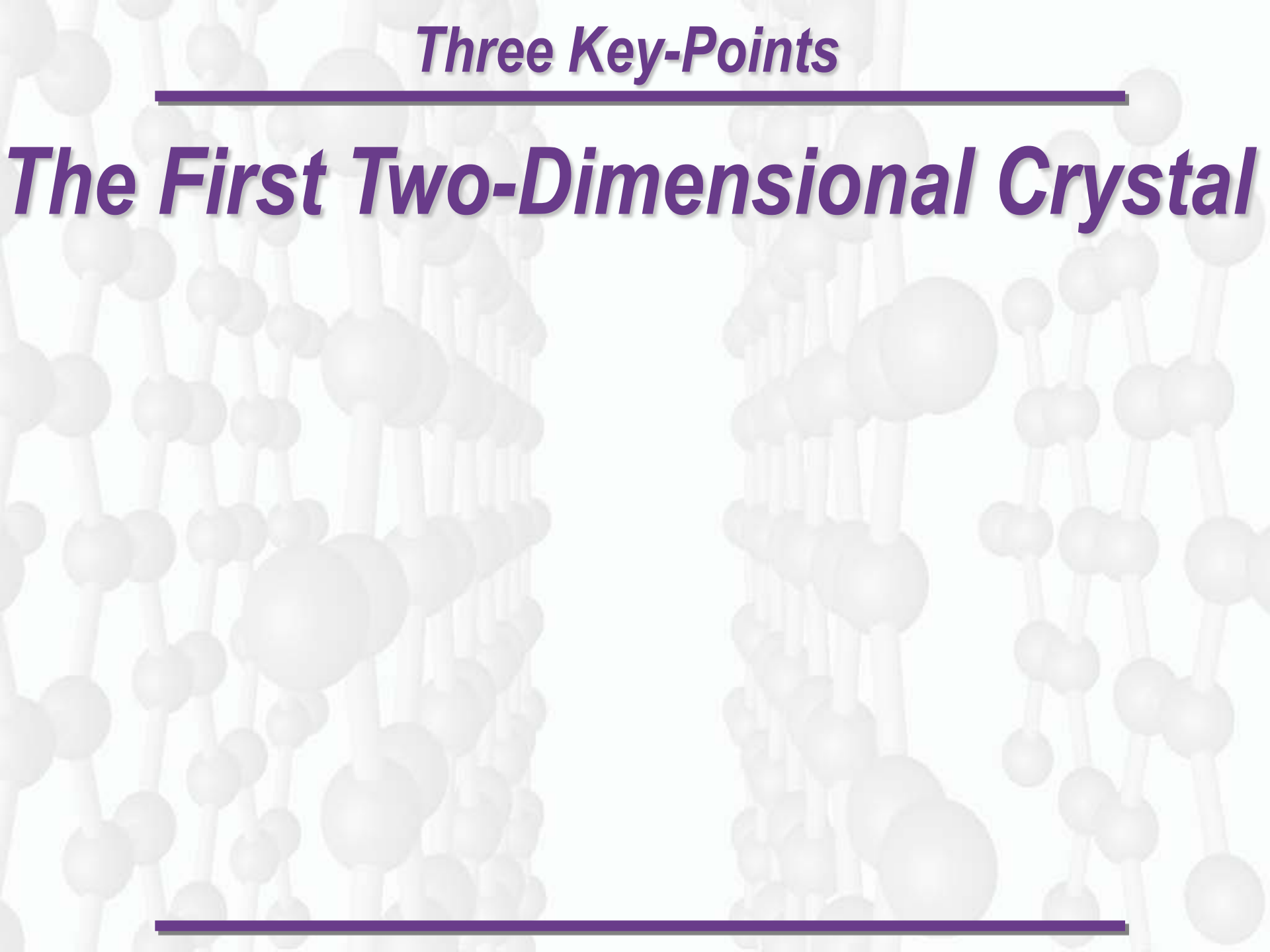
The First Two-Dimensional Crystal

Unusual Electronic Properties

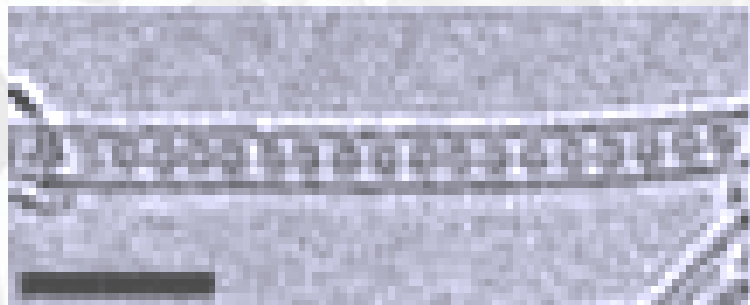
Promising For Applications

Three Key-Points

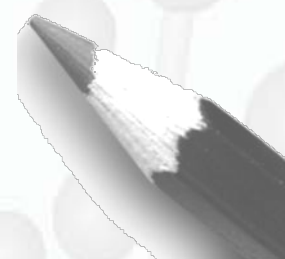
The First Two-Dimensional Crystal



Two-Dimensional Form of Carbon



<http://www.stanford.edu/group/GGG/1D.html>



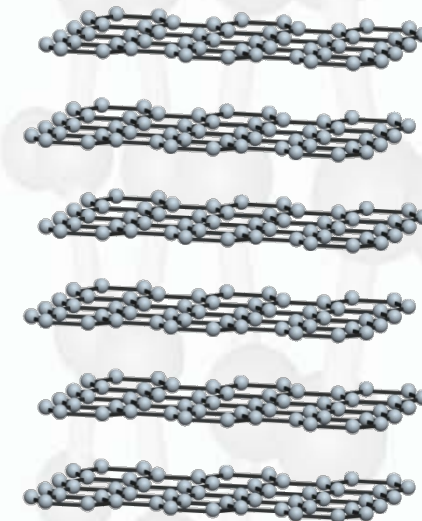
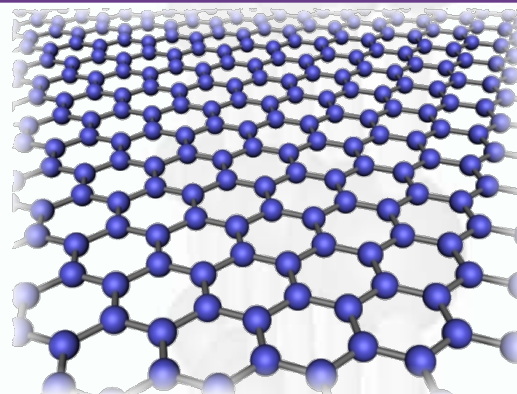
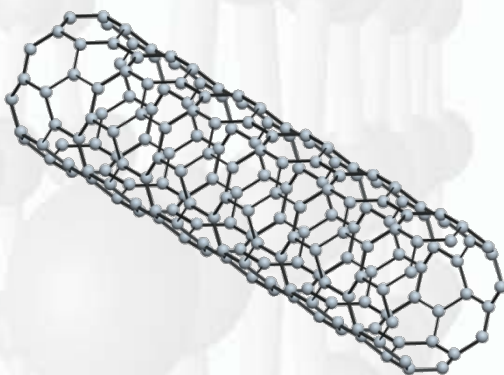
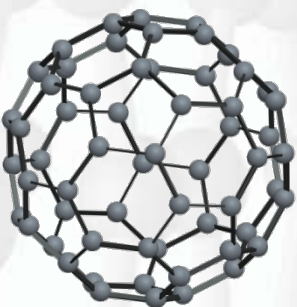
<http://www.chem.uu.se/~vejournal.com/2897.html#mpaf-28395>

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

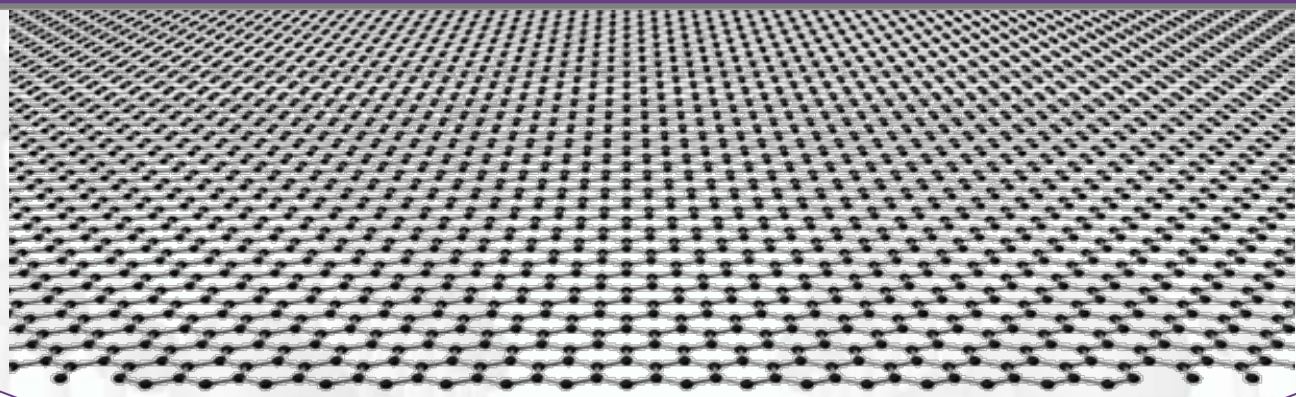
Graphite

1564

Borrowdale

Carbon Allotropes

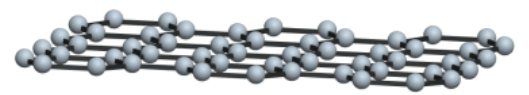
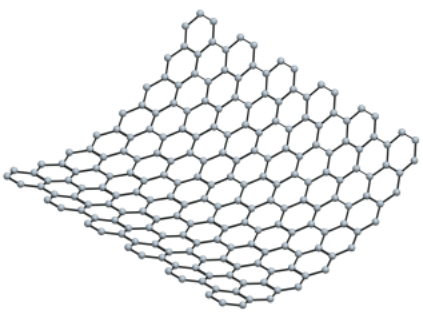
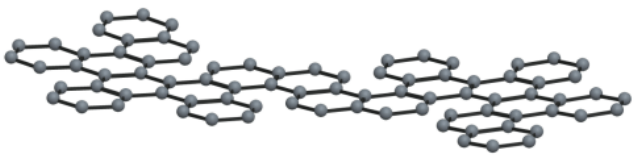
2d
Graphene



0d

1d

3d

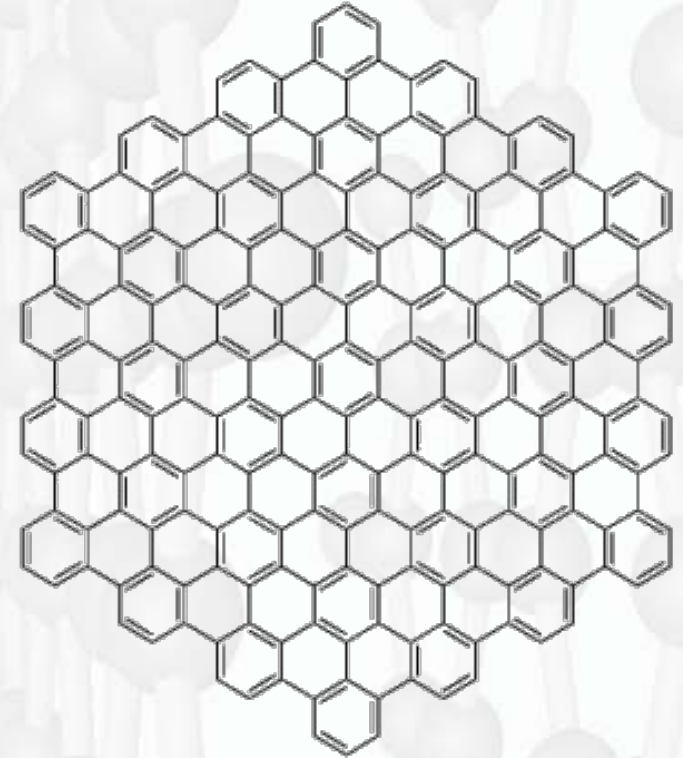
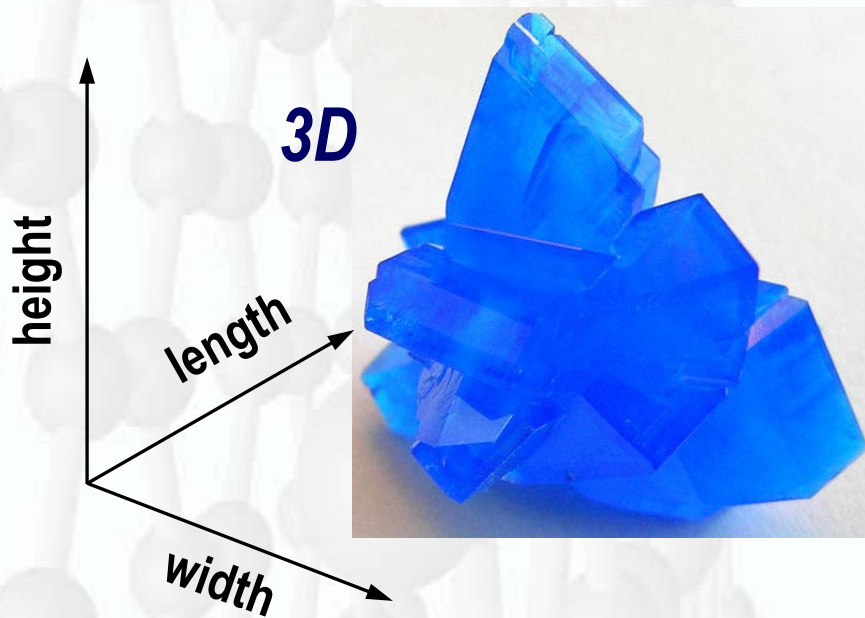


“Buckyball”

Carbon Nanotube

Graphite

All Natural Materials Are 3D

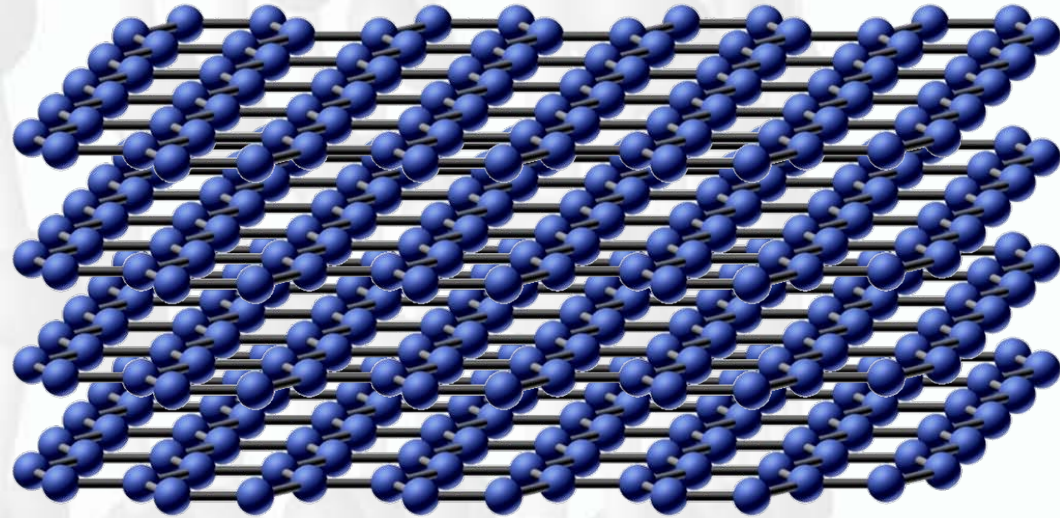


*largest known
flat hydrocarbon:
222 atoms or 37 benzene rings*

(K. Müllen 2002)

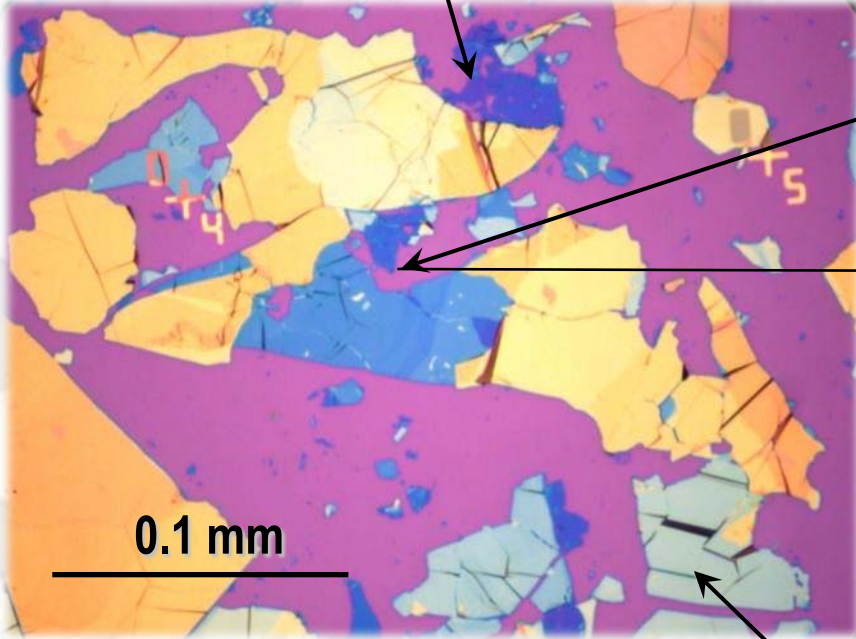
Can We Cheat Nature?

Slicing by way of a horizontal plane

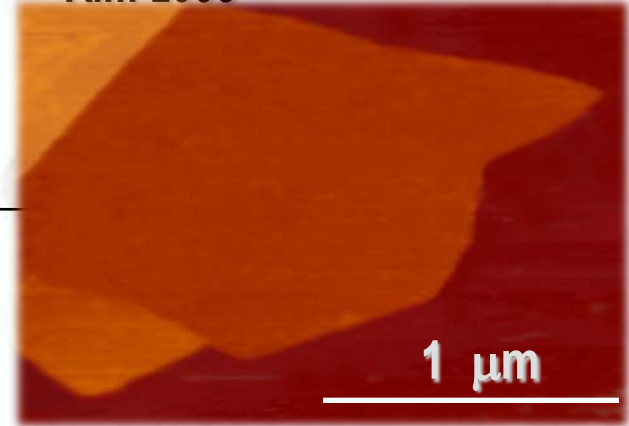


Into The Pencil Trace

1-5 layers Manchester 2004



10 to 30 layers
Kim 2005



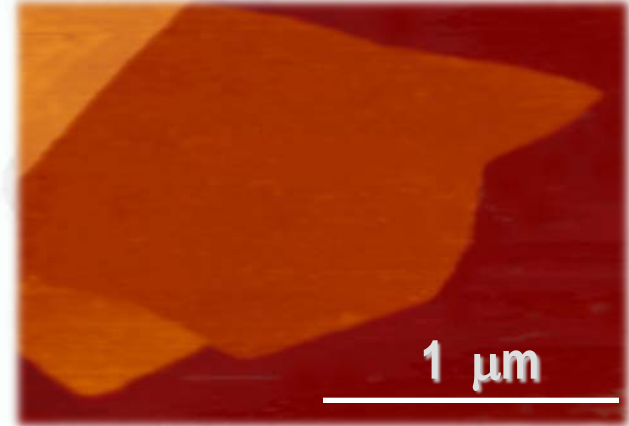
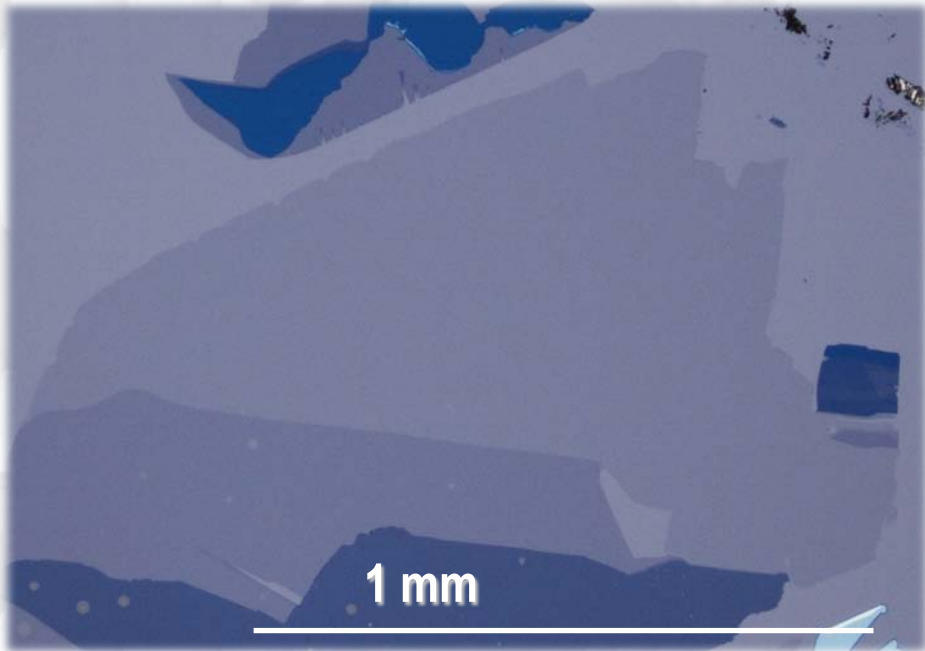
first 2D material demonstrated
- Manchester, Science '04



graphite trace
on oxidized Si wafer

~100 layers
Kurtz 1991
Dujardin 1997
Ohashi 1997
Ruoff 1999

Into The Pencil Trace



***first 2D material demonstrated
- Manchester, Science '04***



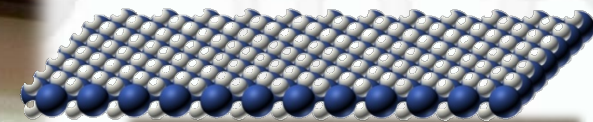
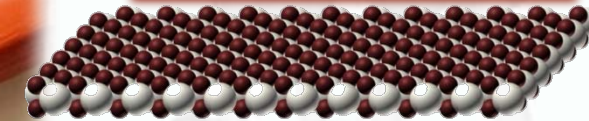
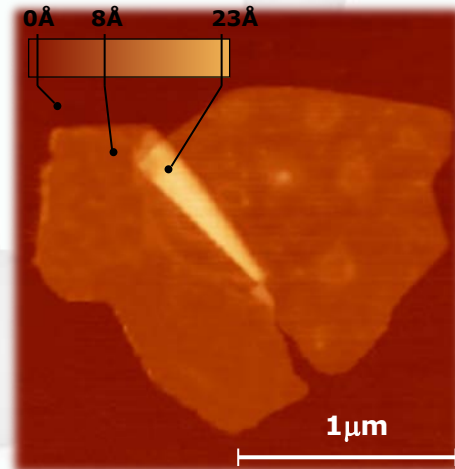
***graphite trace
on oxidized Si wafer***

Other 2D Crystals

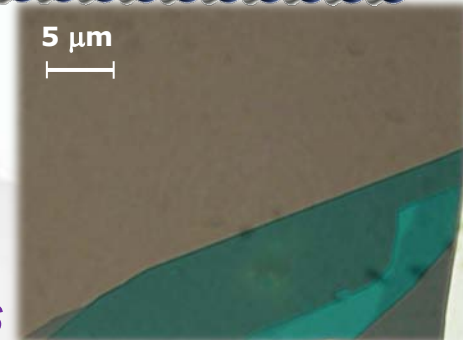
2D boron nitride in optics

2D NbSe₂ in AFM

From 3D systems



5 μm

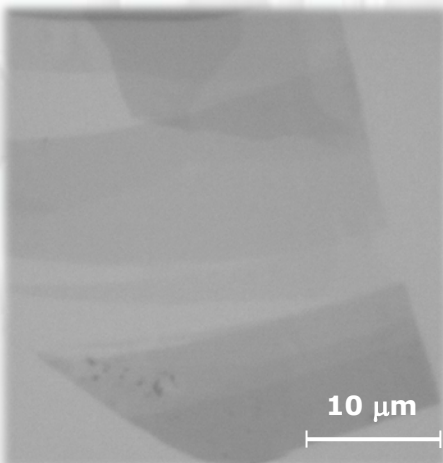


Novoselov et al PNAS (2005)

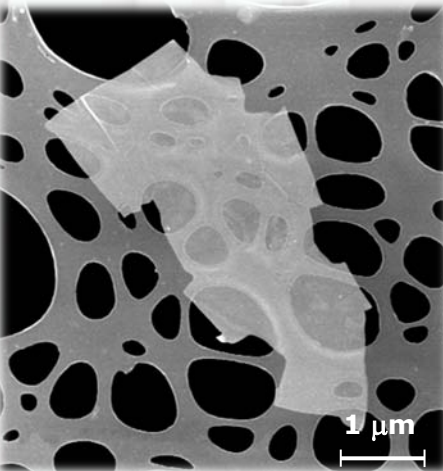
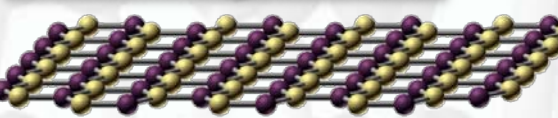
**High Quality
Different From 3D Precursor**

2D Bi₂Sr₂CaCu₂O_x in SEM

2D MoS₂ in optics



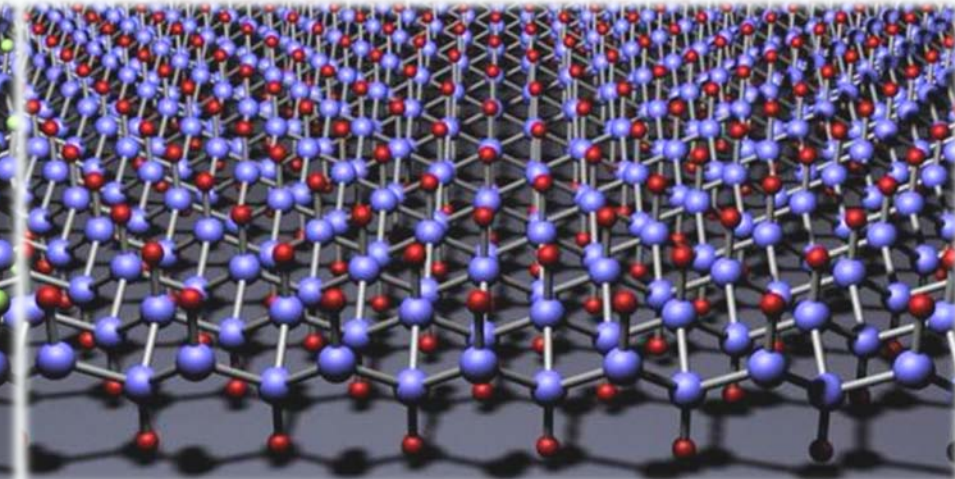
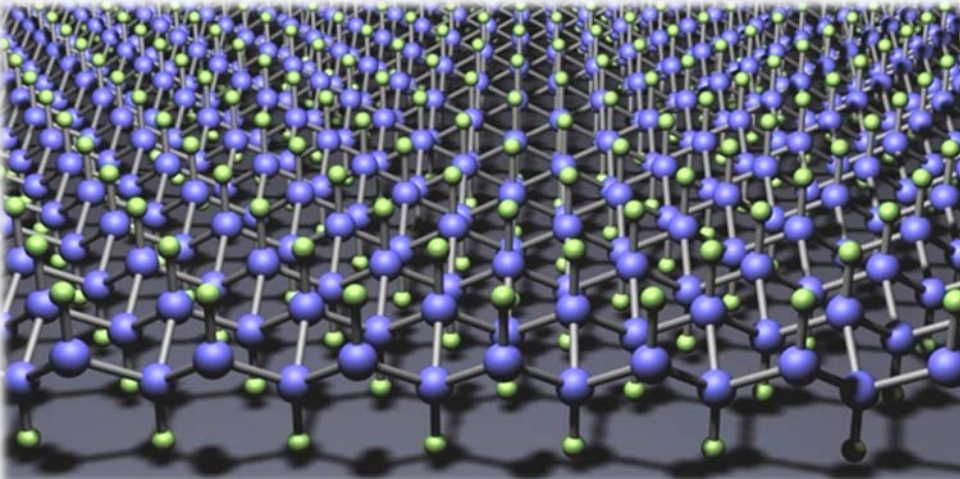
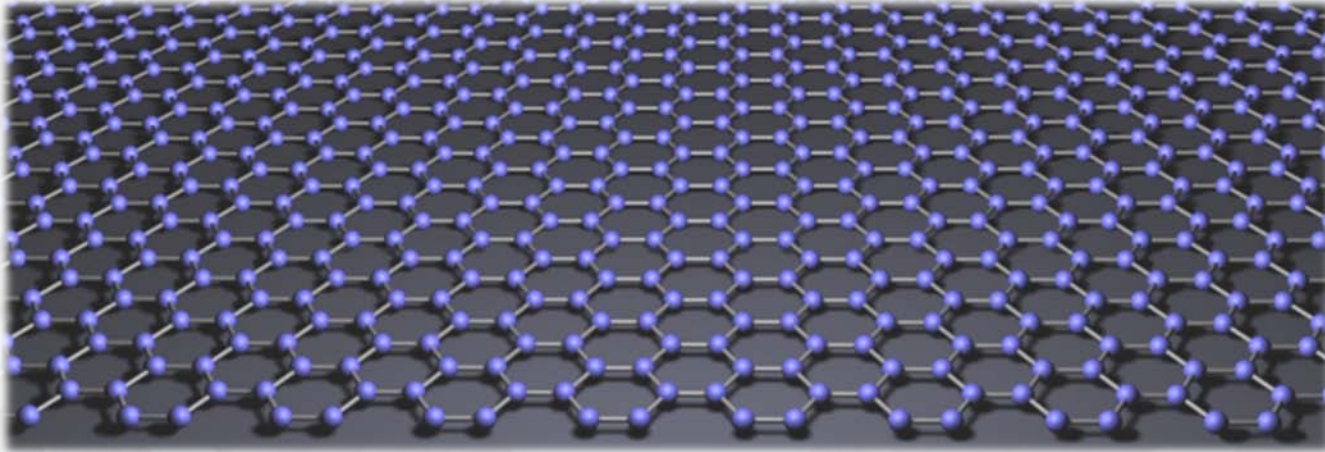
10 μm



1 μm



Other 2D Crystals



FLUOROGRAPHENE (graFane)

Manchester Small '10

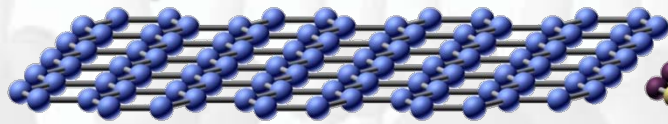
graphane

Manchester Science '09

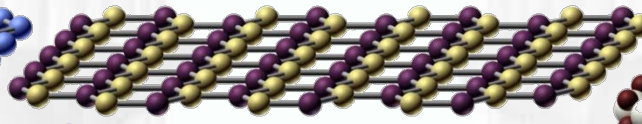
New Class of Crystalline Materials

2-DIMENSIONAL ATOMIC CRYSTALS

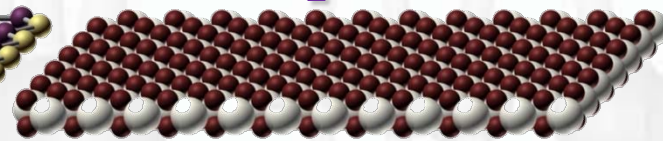
Studied (???):
Graphene



Lightly Touched:
Boron-Nitride

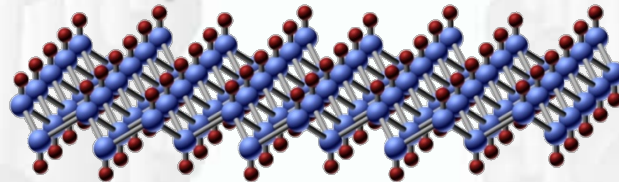


Unexplored:
NbSe₂

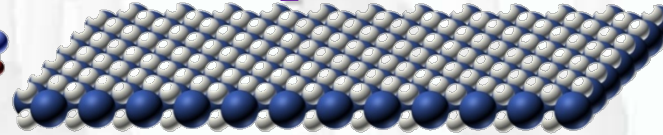


**Large
Variety of
Material
Properties**

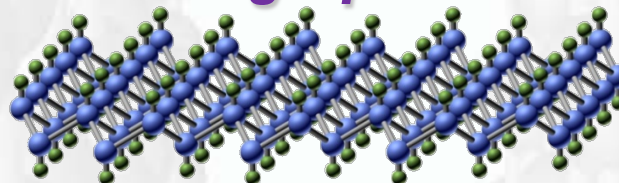
Graphane



MoS₂



Fluorographene

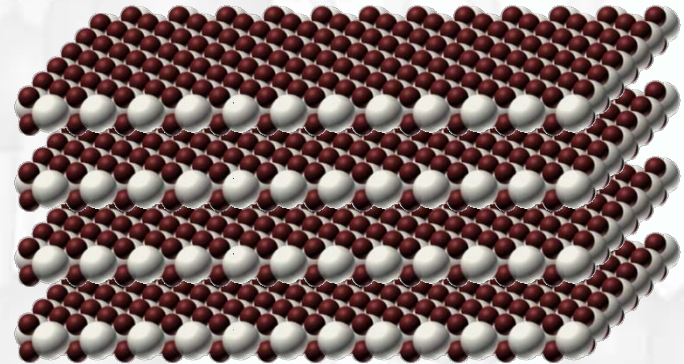
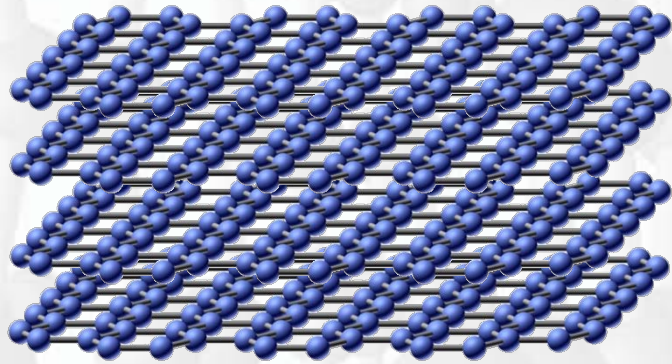


*MgB₂
BiSCCO*

...

A Dream: Back From The FLATLAND

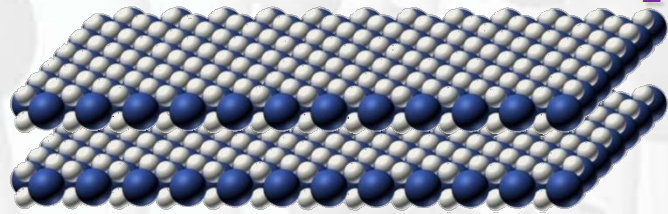
Materials on Demand



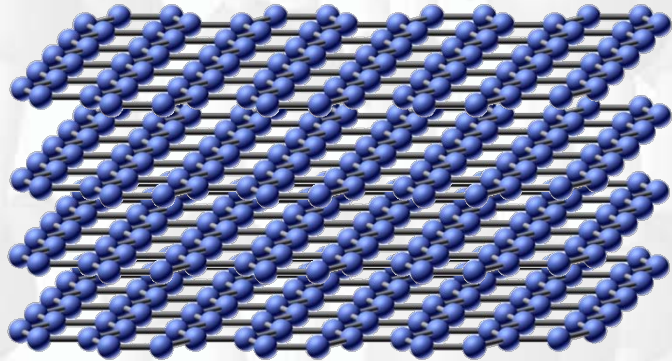
*What kind of properties
would this material possess?*

2D-Crystals-Based *Heterostructures*

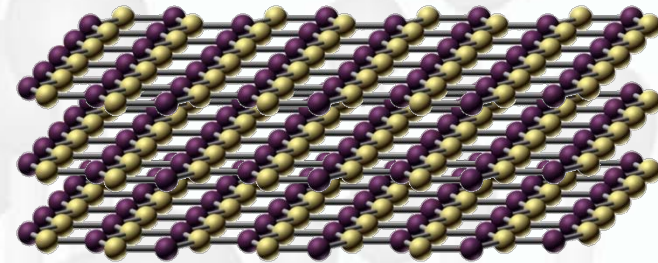
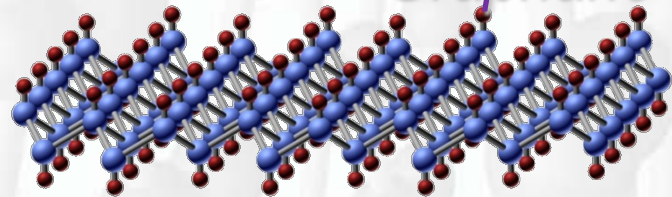
MoS_2



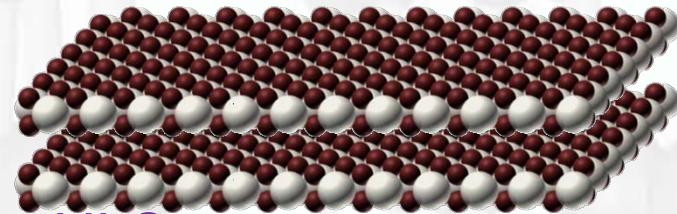
Graphene



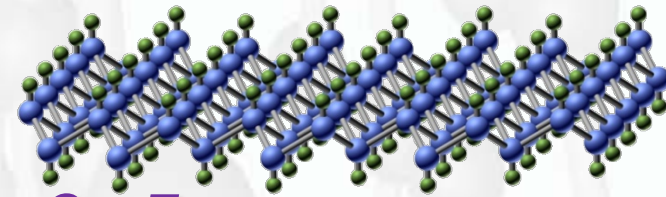
Graphane



Boron-Nitride



NbSe_2



GraFane

2D-Crystals-Based **Heterostructures**

Graphene

ultimately thin

linear gapless spectrum

*chemically active
(new materials:*

graphane, flurographene)

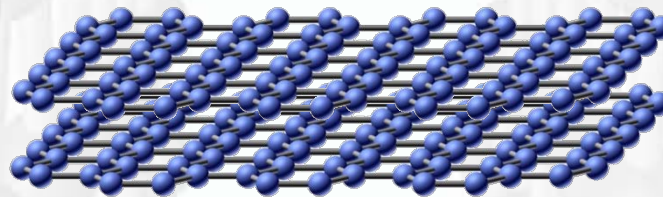


New Material: **Bilayer Graphene**

two layers – can slide

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

chemically less active



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)

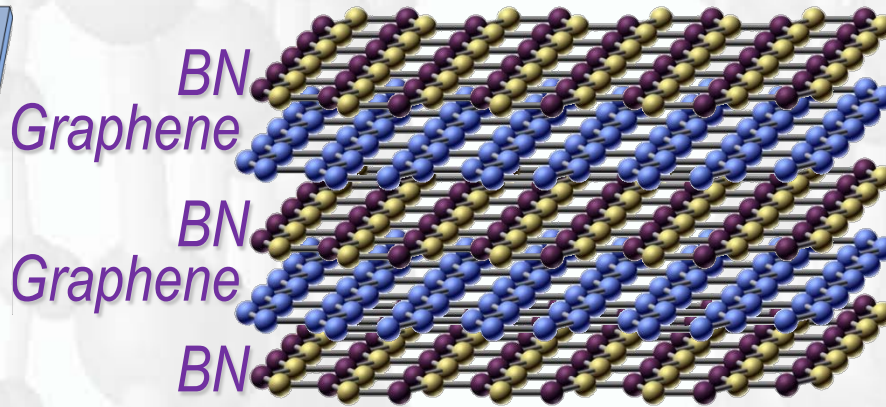
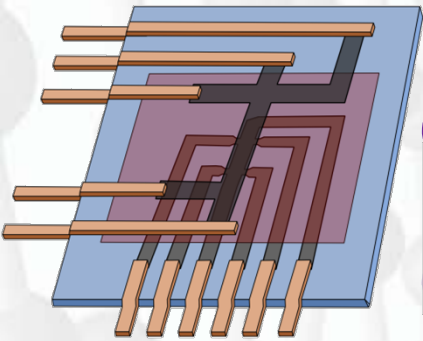
Graphite

cleaves easily

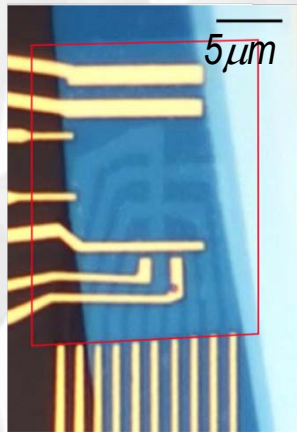
semimetal

inert

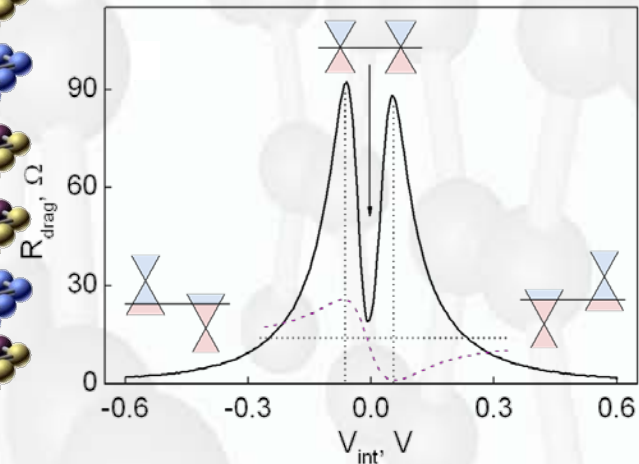
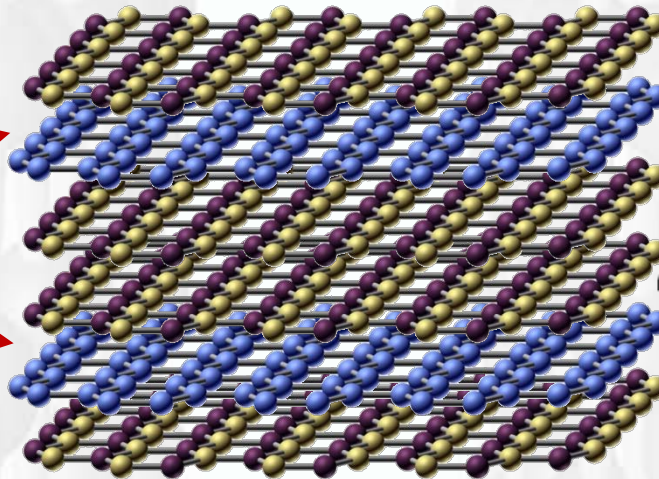
2D-Crystals-Based Heterostructures



Strong Coupling
(tunnelling regime)



Weak Coupling
(Coulomb interaction)



Coulomb Drag

Three Key-Points

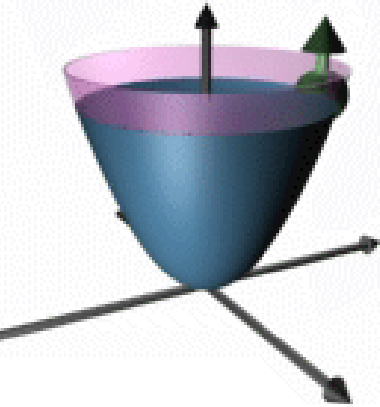
Unusual Electronic Properties

New Types of Quasiparticles

“Schrödinger fermions”

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

Electron metal



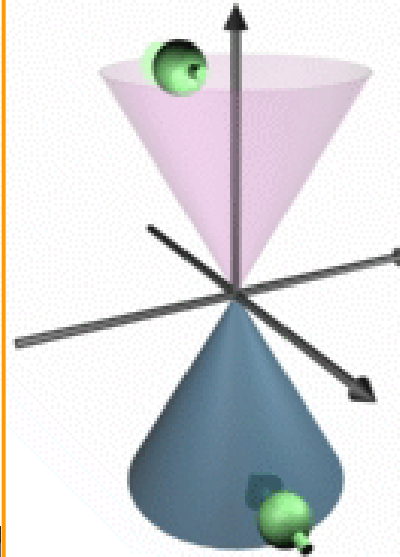
Hole metal



massless

Dirac fermions

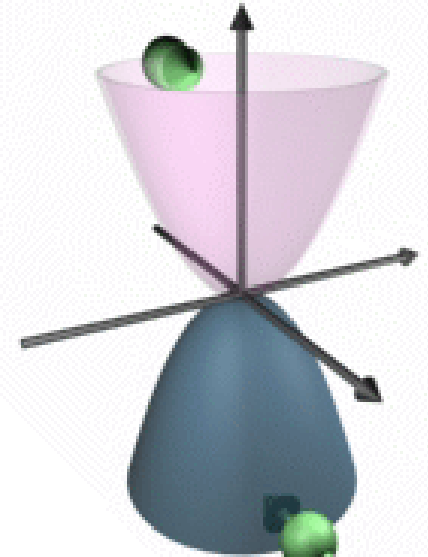
$$\hat{H} = v_F \vec{\sigma} \cdot \hat{p} \quad \text{Semenoff 1984}$$



massive

chiral fermions

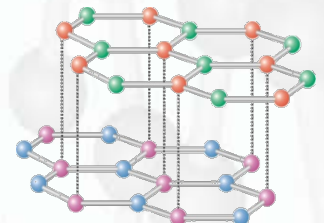
$$\hat{H} = \vec{\sigma} \cdot \hat{p}^2 / 2m^* \quad \text{Falko 2006}$$



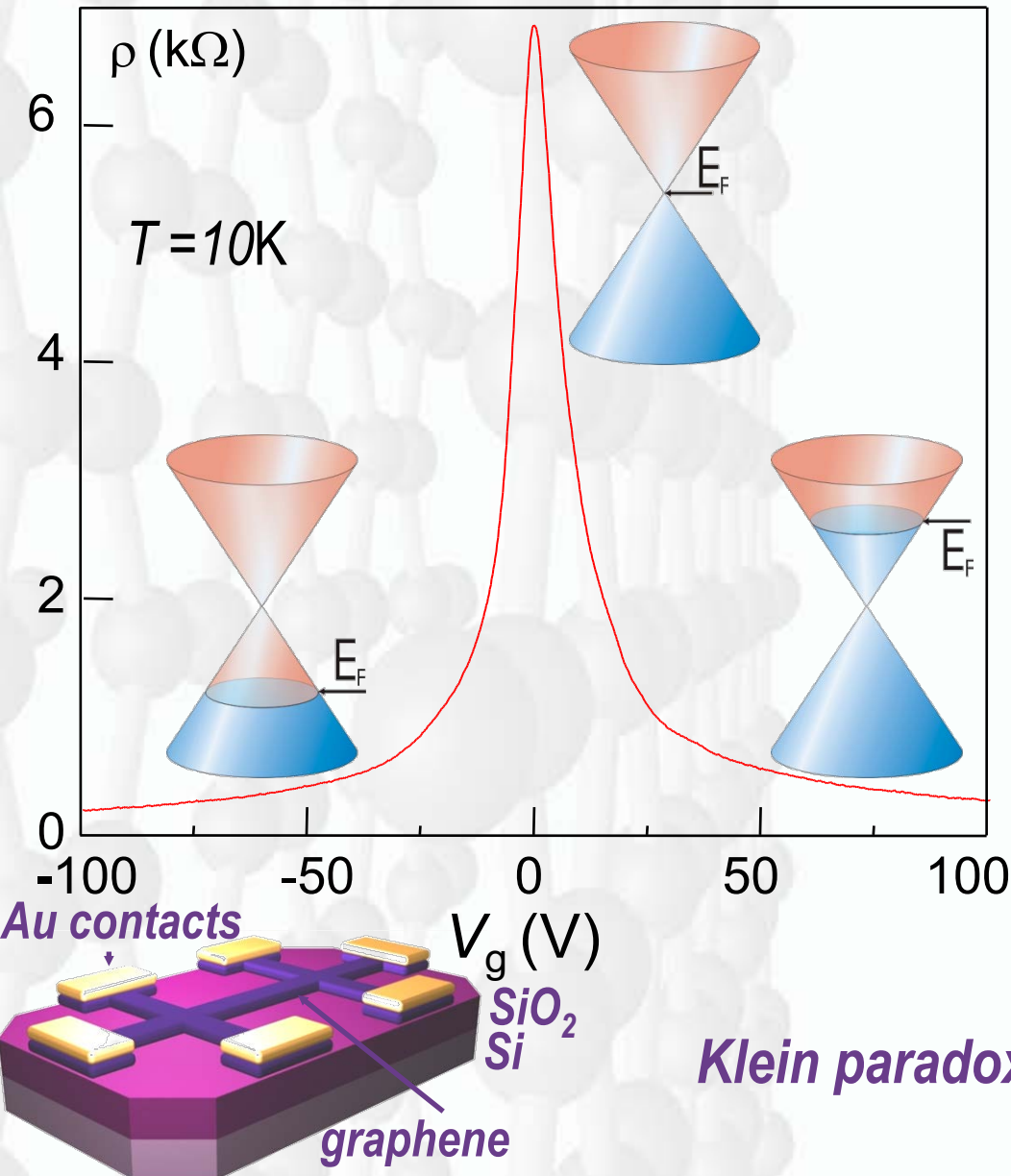
**monolayer graphene
neutron stars
& accelerators**



bilayer graphene



Graphene Field Effect Transistors



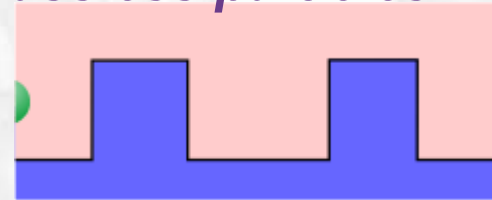
Klein paradox

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

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

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

Massless particles in 2D:



NEVER LOCALIZED

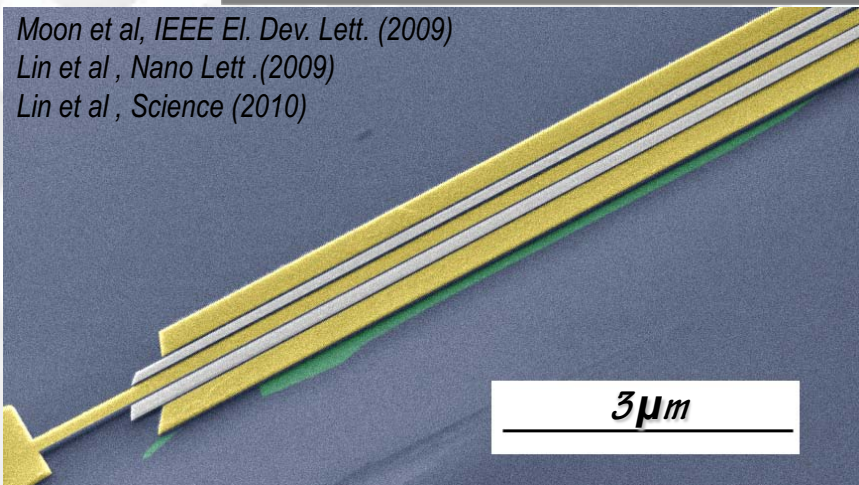
O. Klein, Z. Phys 53,157 (1929); 41, 407 (1927)

M.I.Katsnelson et al Nature Physics (2006)

Young et al Nature Physics (2009)

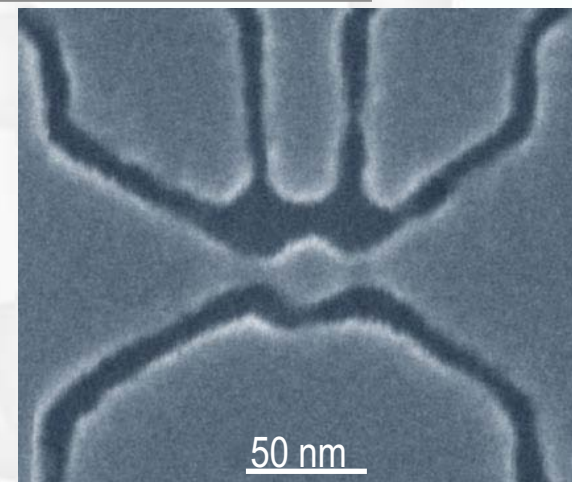
Graphene Transistors

Moon et al, IEEE El. Dev. Lett. (2009)
Lin et al, Nano Lett. (2009)
Lin et al, Science (2010)



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)



ballistic transport between
source & drain: **THz range**
ultra high-F analogue transistors:

HEMT design;

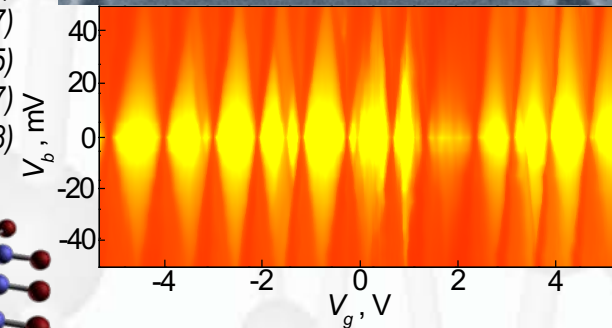
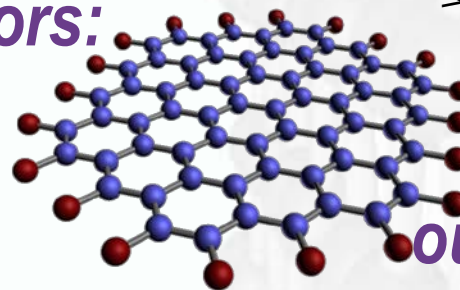
“standard” mobilities;

on-off ratio: ~100

Manchester, Science '04

100GHz @ 240nm channel
– better than Si

even with very modest mobility of $1.500 \text{ cm}^2/\text{V}\cdot\text{s}$



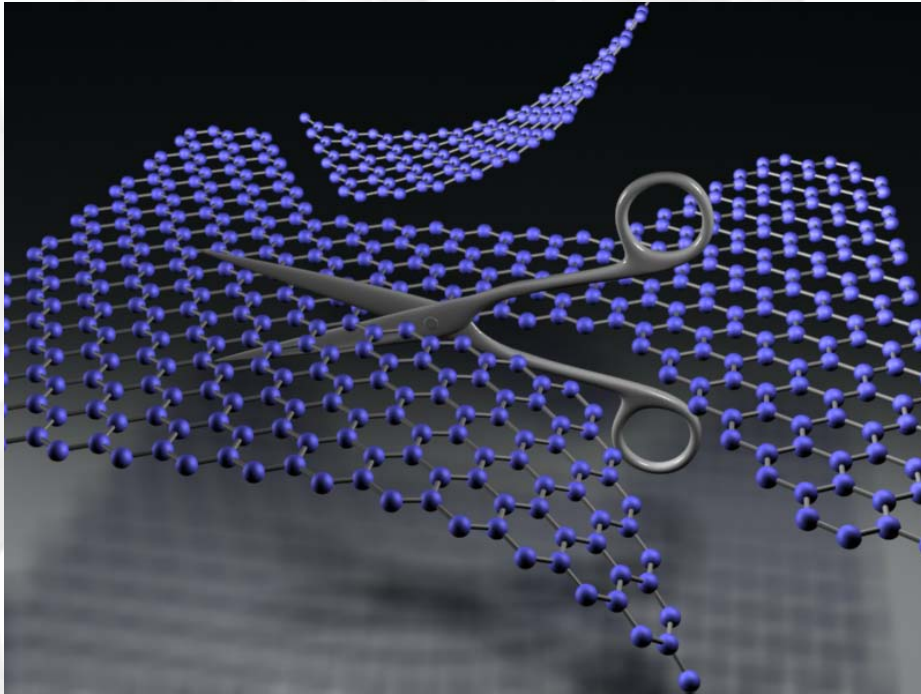
our smallest QD ~ 1nm

Top-Down Molecular Electronics

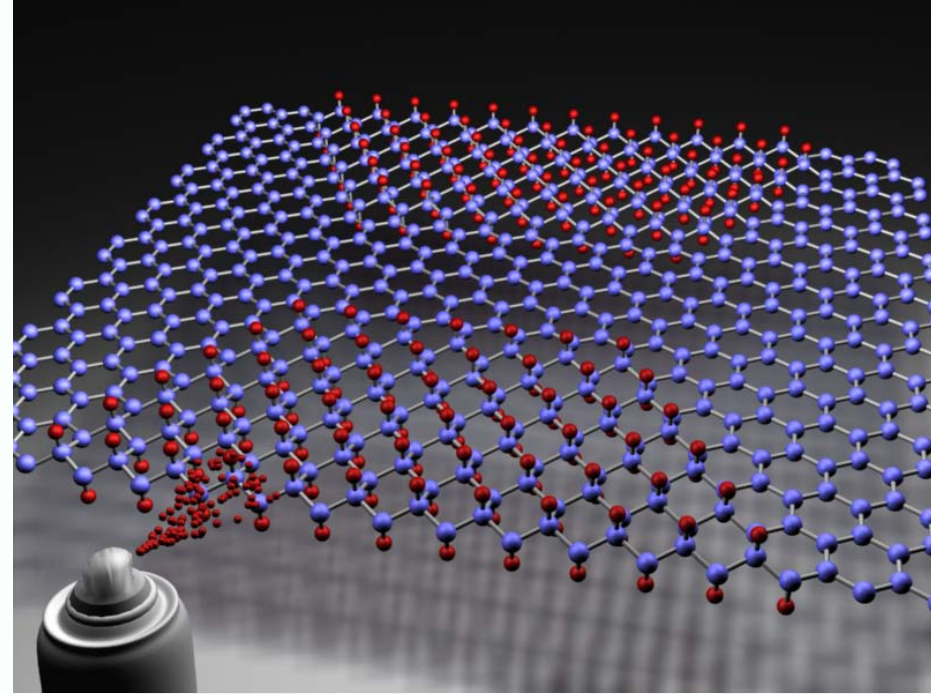
- Only few benzene rings
- Remarkably stable
- Sustains large currents

Paper Cutting vs Paper Painting

Nanoribbons, Quantum Point Contacts, Quantum Dots

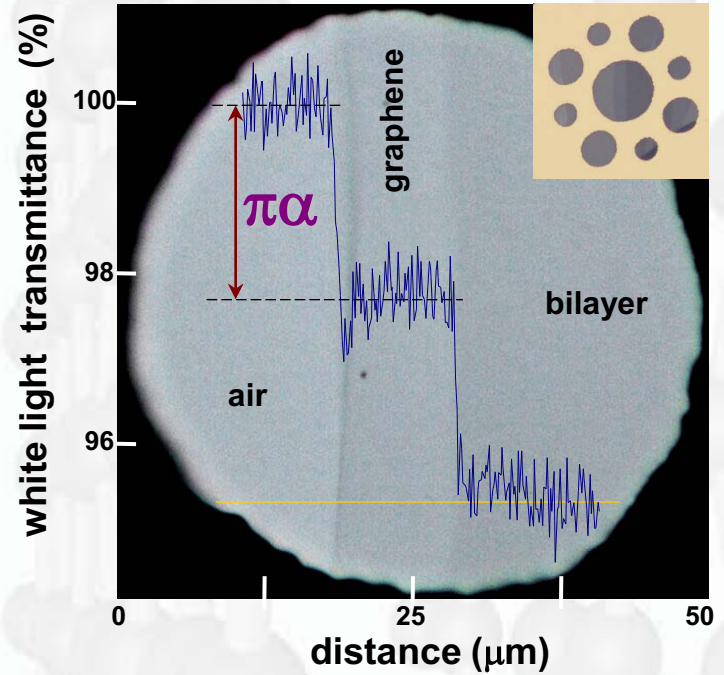
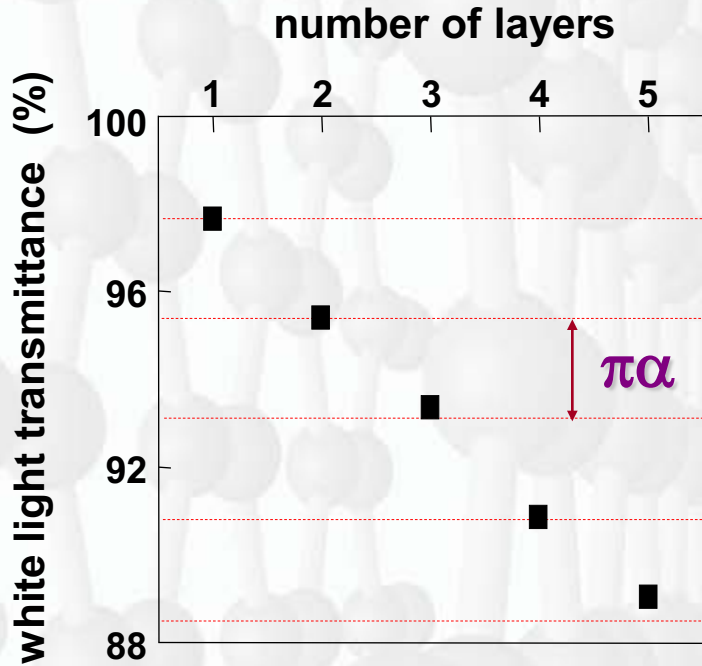


Reactive Plasma Etching



Hydrogenation

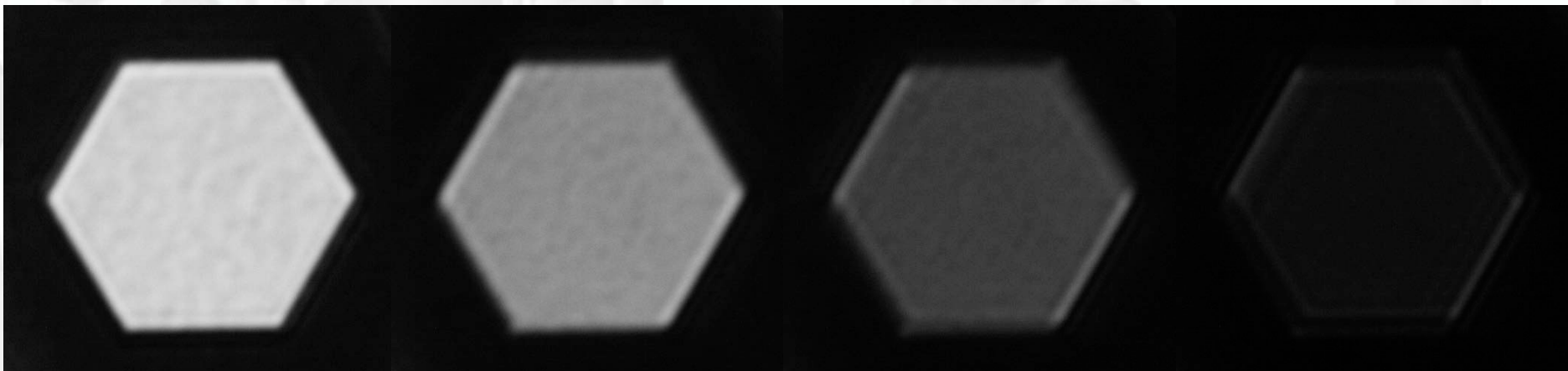
Visualisation of Fine Structure Constant



*the fine structure constant
observed
“with a naked eye”
 $\alpha = 1/137 (\pm 2\%)$*

*Do it at home
 $\pi\alpha = 3.14.. \times 1/137$*

Graphene-based Liquid Crystal Display



$V=0V$

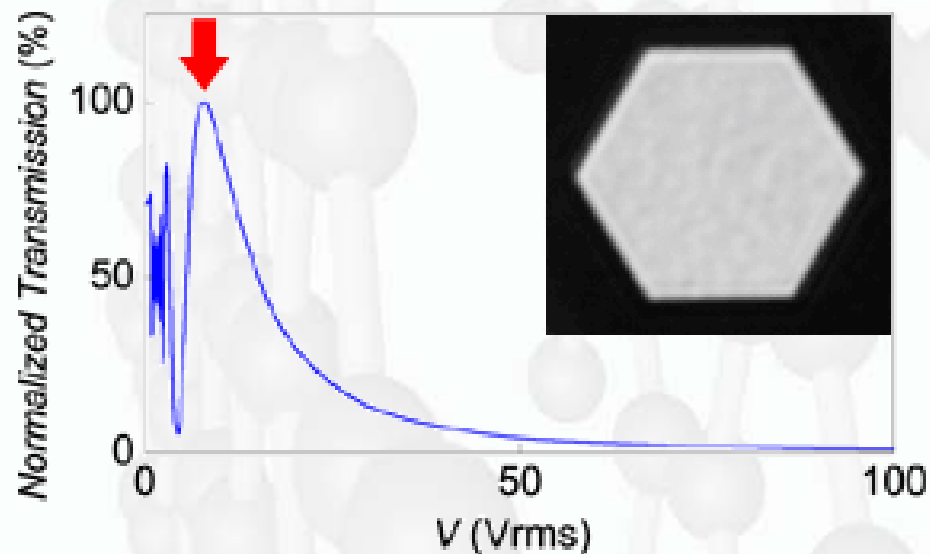
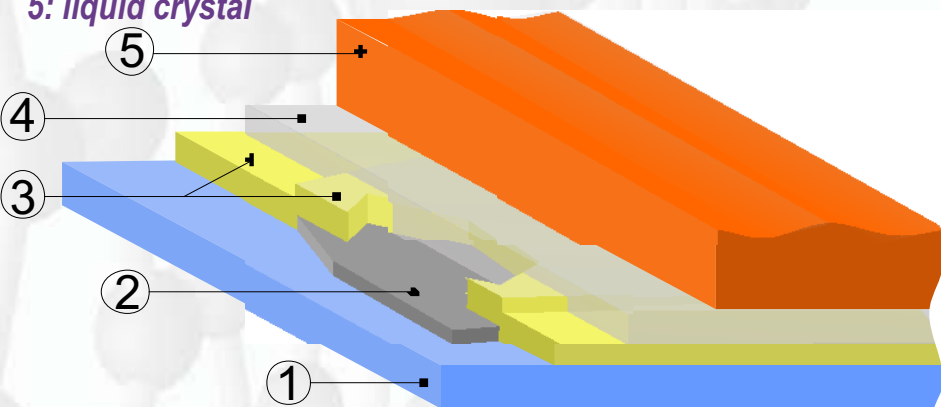
$V=15V$

$V=30V$

$V=100V$

High Transparency
High Conductivity
Inert Material

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



Three Key-Points

Promising For Applications

What Has Graphene Ever Done For Us?

• Create Workplaces

• Provide Entertainment



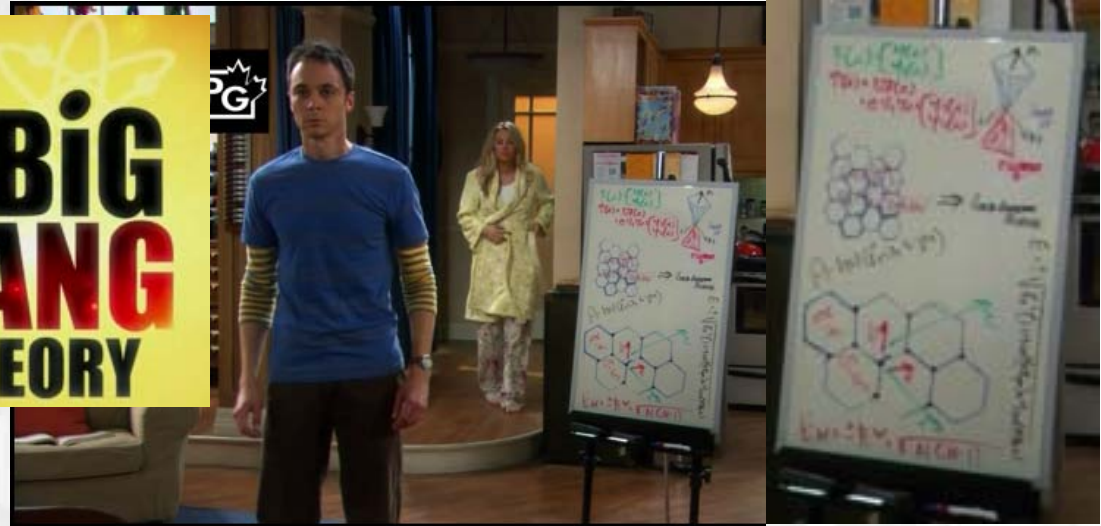
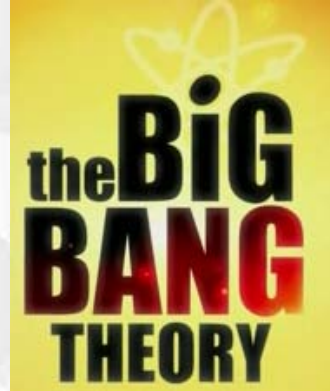
GRAPHENE INDUSTRIES



GRAPHENE RESEARCH



GRAPHENE SUPERMARKET



• Give Shelter

Tallahassee, Florida, USA



2268 Graphene Lane, Tallahassee FL 32310

Condo/Townhome/Co-Op for Sale for \$119,900 with 3 bedrooms and 2 full baths, 1 half bath. This 1,617 square foot home was built in 2008 on lot size of condo.

Summary

Photos

Map

Area



Save



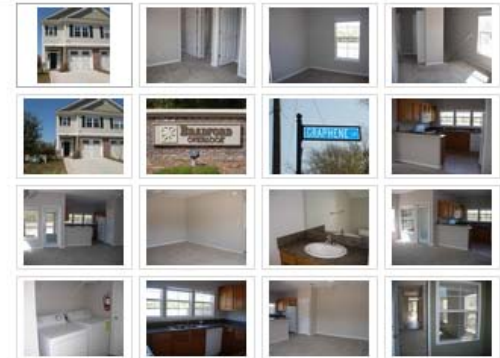
Print



Email friend



Share



Not Free Standing



View all 20 large photos



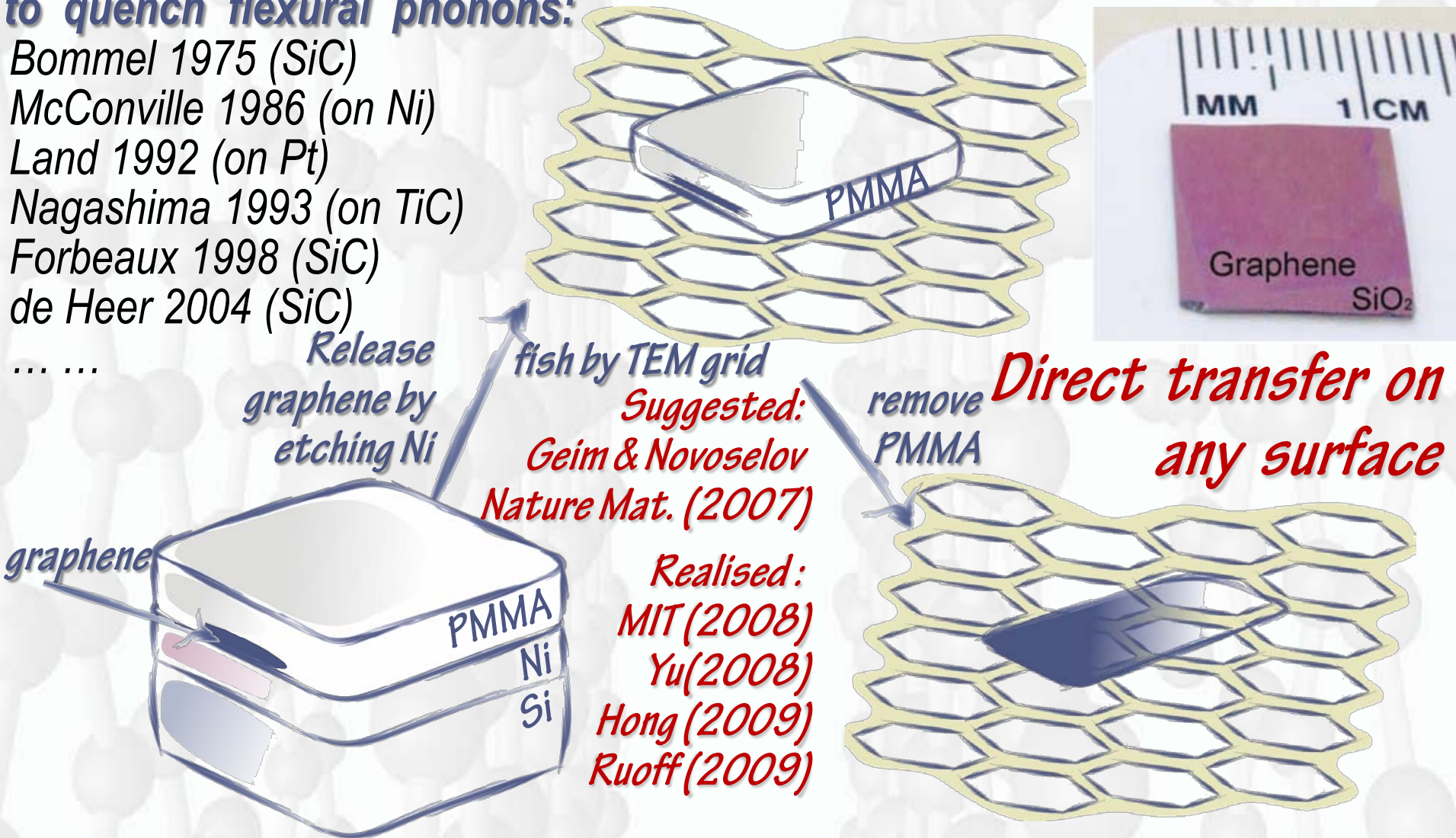
Mass Production of Graphene

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)

... ..



First Graphene Products are Already There

www.grapheneresearch.com/Category/9-graphene-membranes.aspx

GRAPHENE RESEARCH

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British Pound

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GRAPHENE MEMBRANES

Graphene membranes on TEM grids are available as shown in the pictures below. The grids is 3.05mm in diameter and 2000 mesh which means the size of individual cell is about $7\mu\text{m} \times 7\mu\text{m}$.

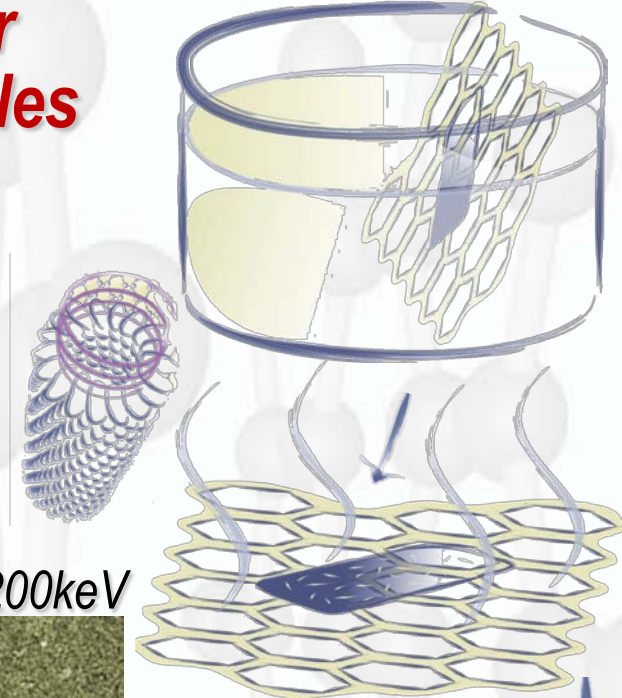
monolayer 10µm

monolayer 20µm

If you have any questions or requirements, please feel free to contact us.

Support for Biomolecules in TEM:

**Ultra Strong
Ultra Thin
Crystalline**



https://graphene-supermarket.com/CVD-Graphene-TEM-grids/

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CVD Graphene™ TEM grids

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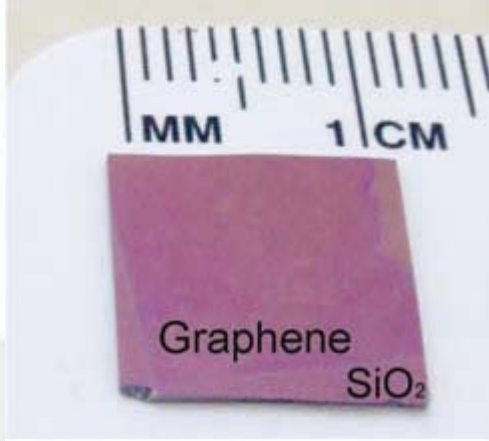
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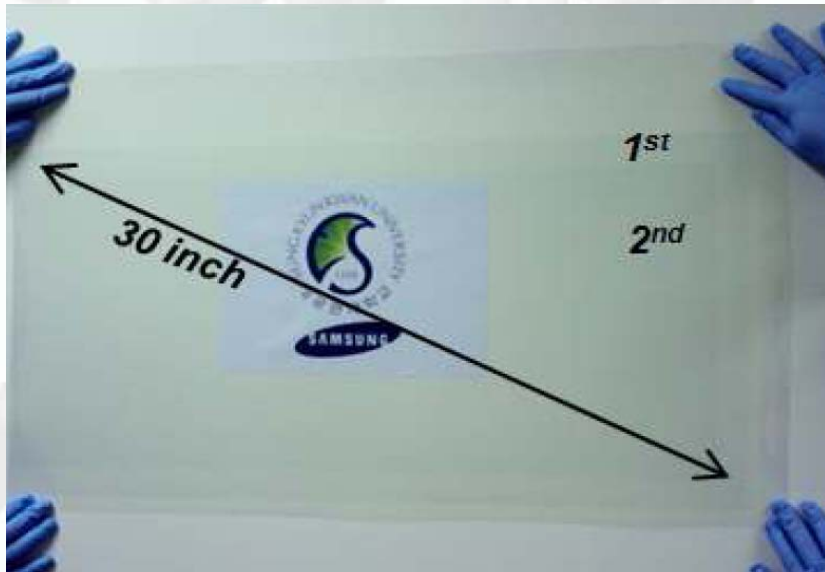


Tobacco Mosaic Virus on graphene Manchester 2010

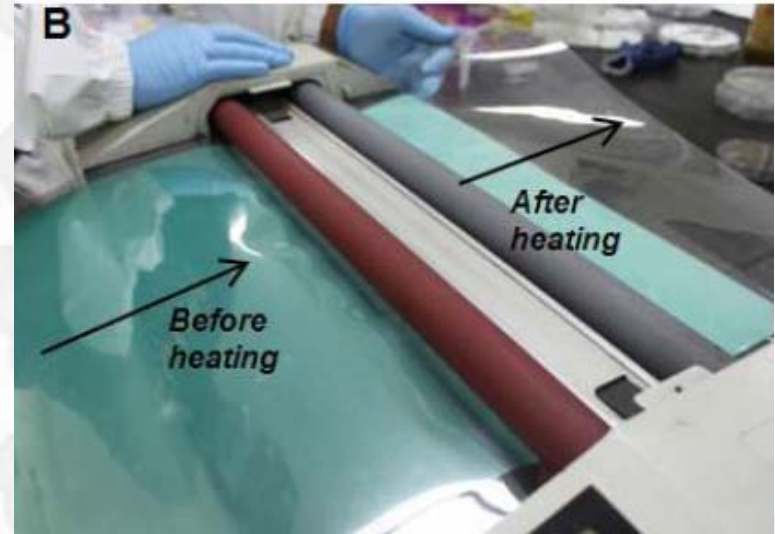
Mass Production of Graphene



CVD growth & transfer are well developed



$\rho \sim 40 \Omega/\square$ transparency $\sim 90\%$
 $\mu \sim 5,000 \text{ cm}^2/\text{Vs}$



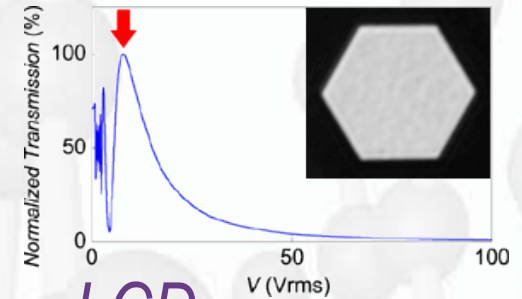
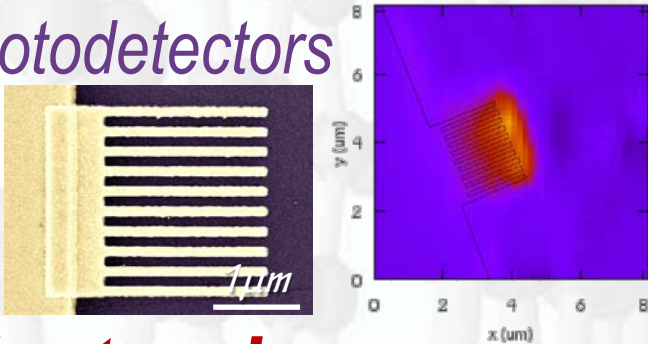
Kim, et al Nature (2009); Li et al Science(2009)

All Major Applications are Realistic

Photovoltaics

(Samsung roadmap: 2012)

Photodetectors



LCD



Wang Nano Lett. (2008)

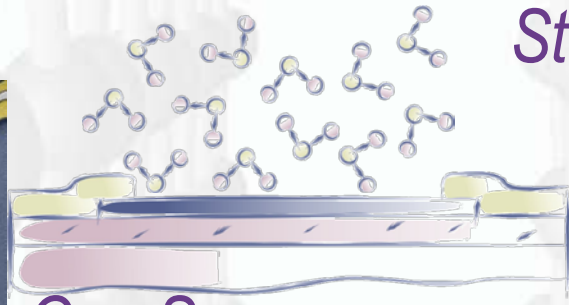
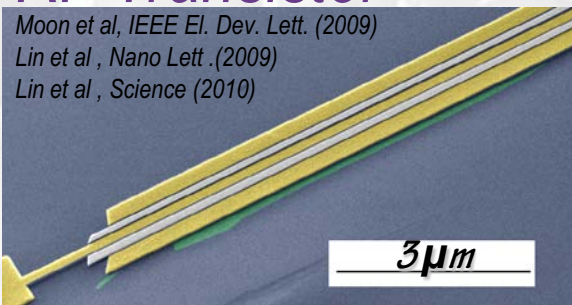
Touch-screens

SolarCells

Electronics

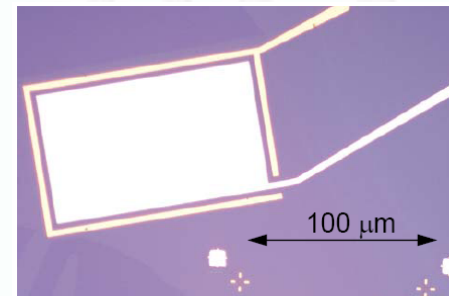
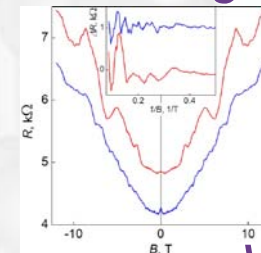
RF Transistor

Moon et al, IEEE El. Dev. Lett. (2009)
Lin et al, Nano Lett. (2009)
Lin et al, Science (2010)



Gas Sensor

Strain Gauge



Variable Capacitor

Composite Materials

Mechanically Strong; Conductive; Optically Active

...



A. Geim

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