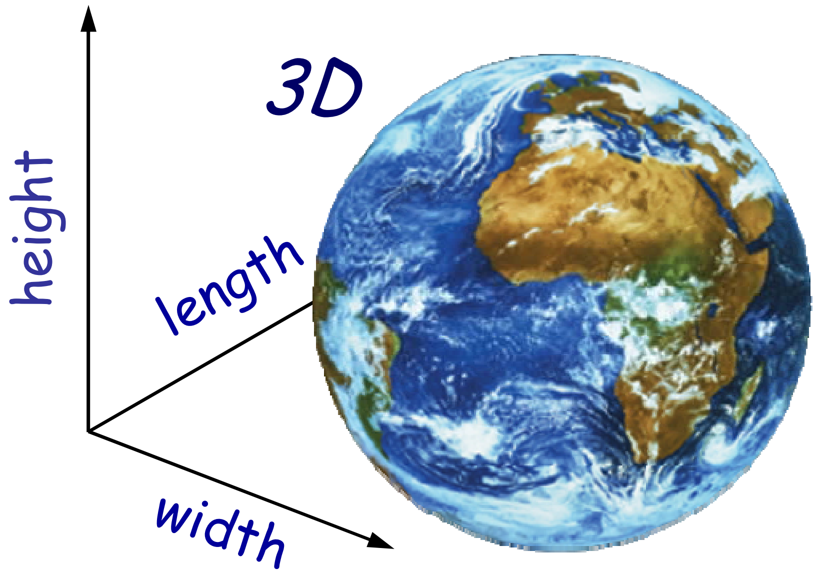
MANCHESTER 1824

The University of Manchester

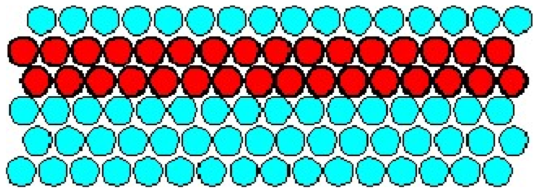
GRAPHENE: status and progress

- basic introduction
  for complete outsiders
- examples of new physics & applications
  for both outsiders & experts

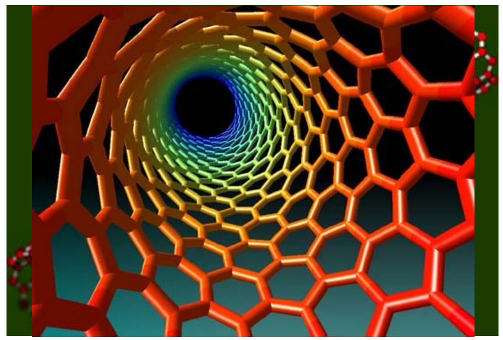
All Natural Object/Materials Are 3D



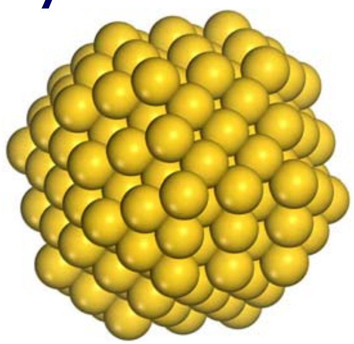
quasi-2D



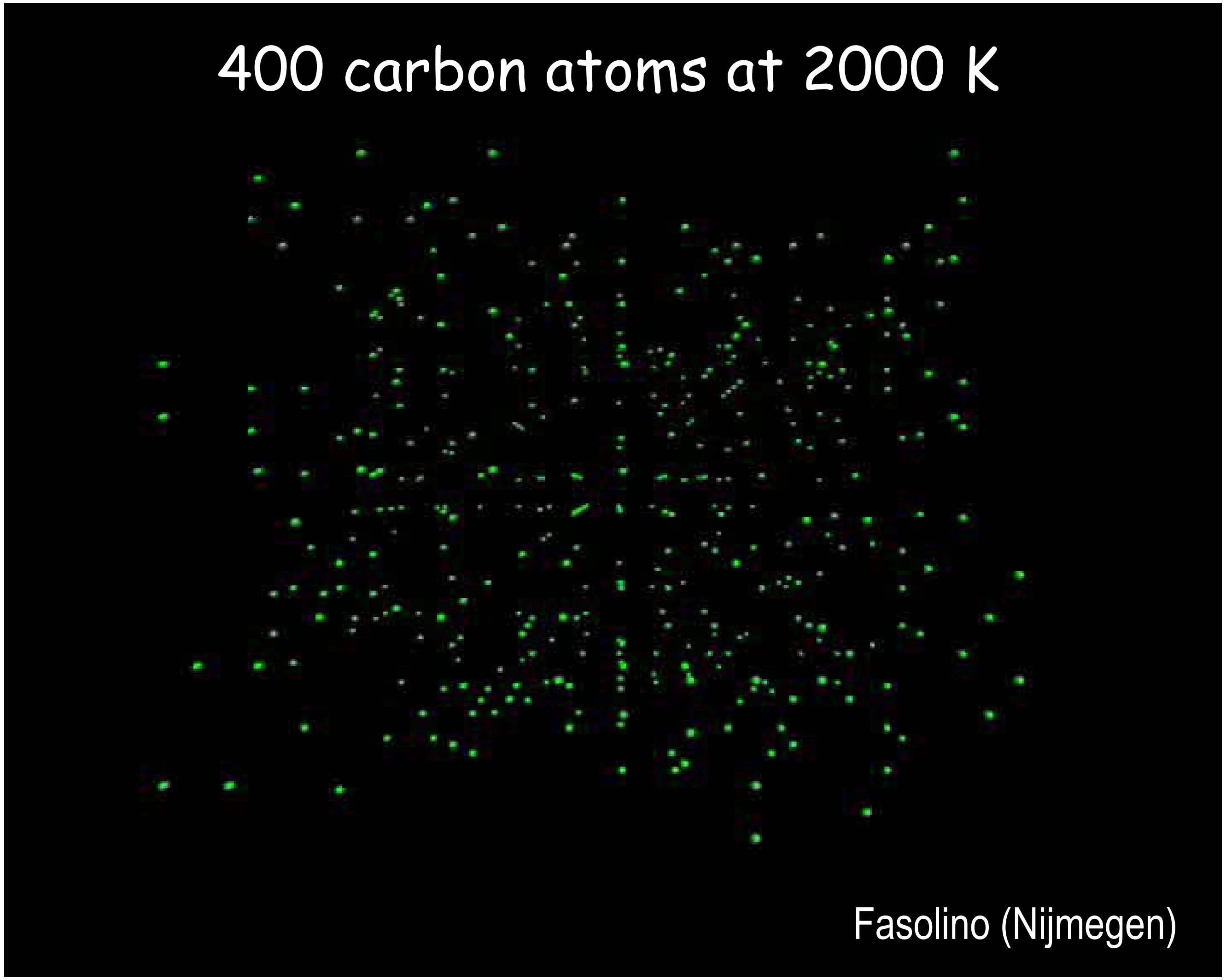
quasi-1D



quasi-0D



NO Bottom-Up Approach



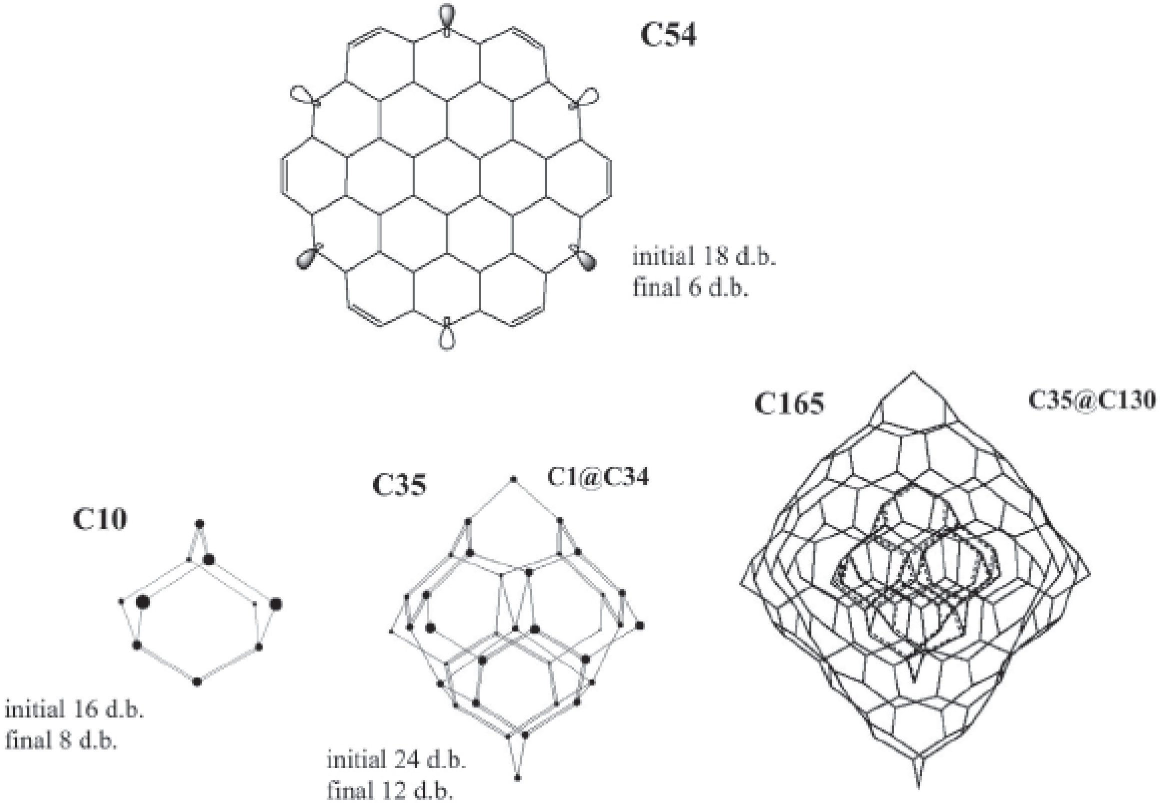
growth
means
temperature
causes
violent
vibrations
destroys
order in 2D

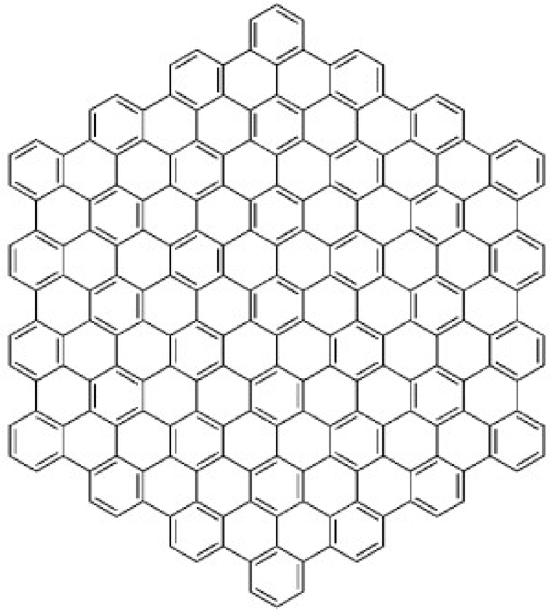
growth of macroscopic 2D objects is <u>strictly</u> forbidden

Peierls; Landau; Mermin-Wagner; ...

(only nm-scale flat crystals possible to grow in isolation)

No Bottom-Up for 2D Crystals



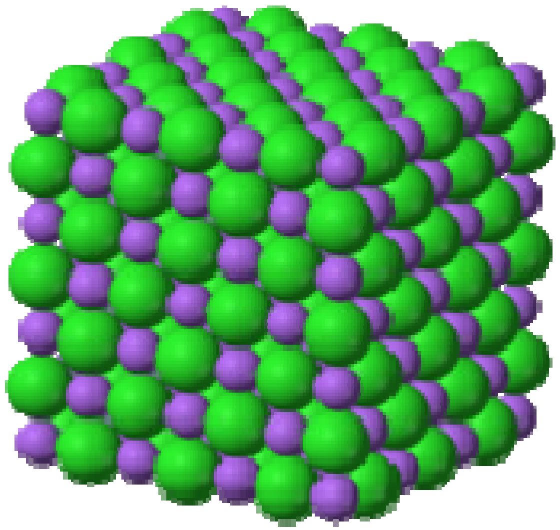


largest known
flat hydrocarbon:
222atoms/37rings
(Klaus Müllen 2002)

graphene:
least stable configuration
for <24,000 atoms (Don Brenner 2002)

above this number (~20 nm), scrolls are most stable

Top-Down Approach

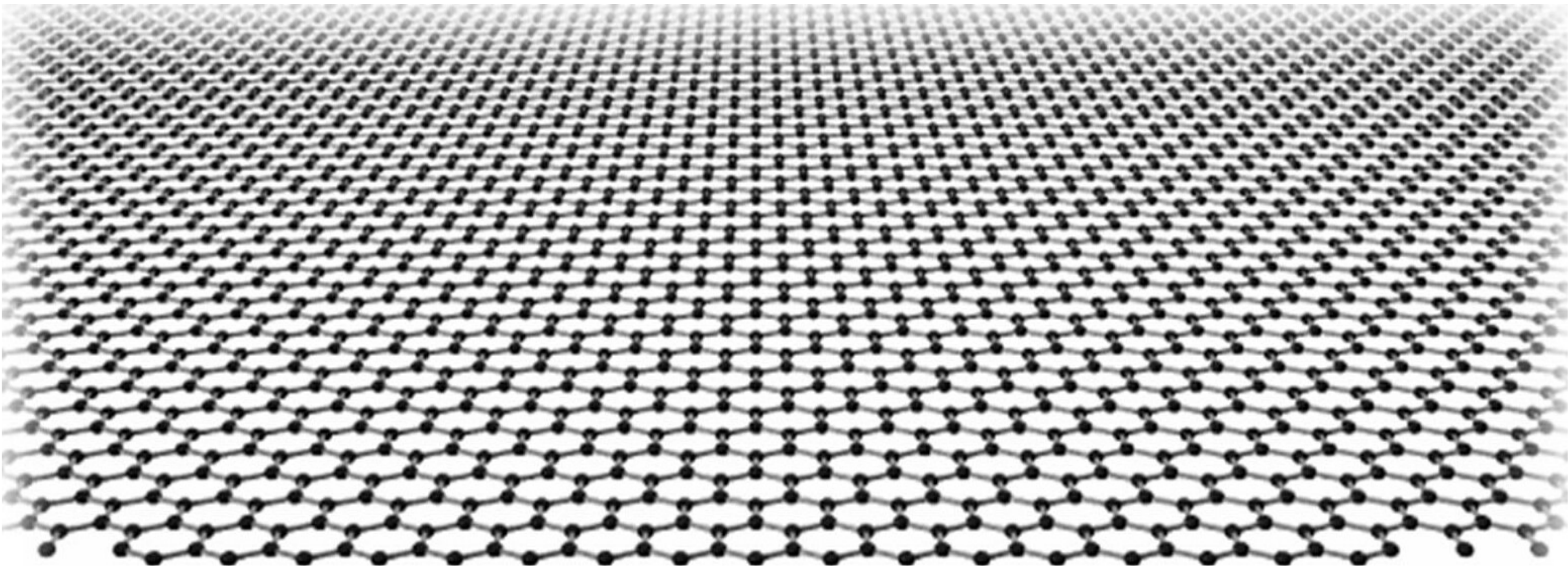


just extract one atomic plane

would it be stable?
would it survive ambient environment?

2½ WAYS OF MAKING GRAPHENE

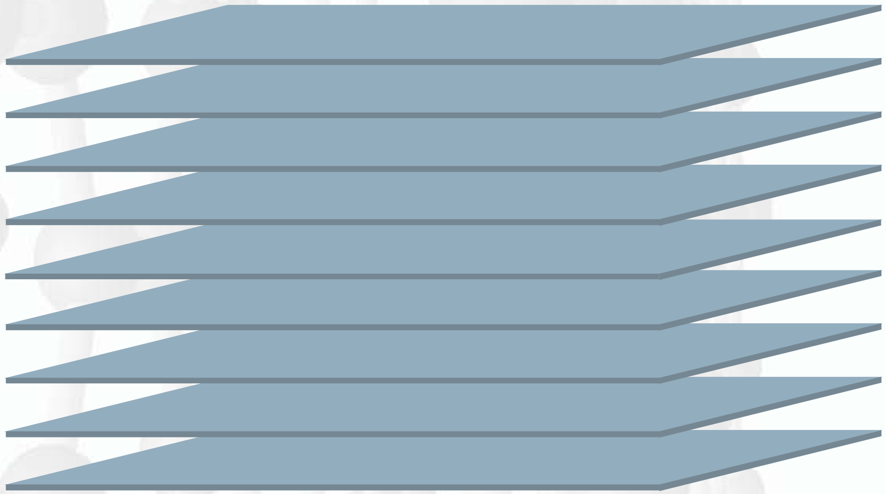
(& OTHER 2D CRYSTALS)



1. MECHANICAL EXTRACTION

Manchester, *Science* 2004; *PNAS* 2005

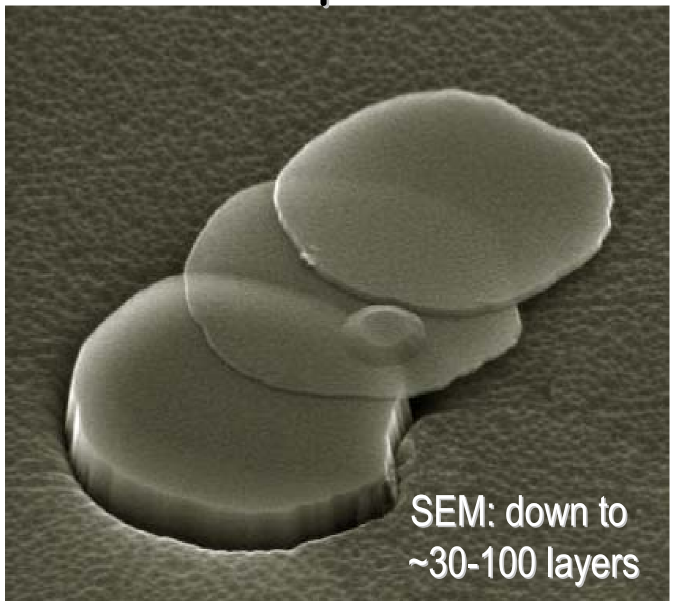
extract individual atomic planes

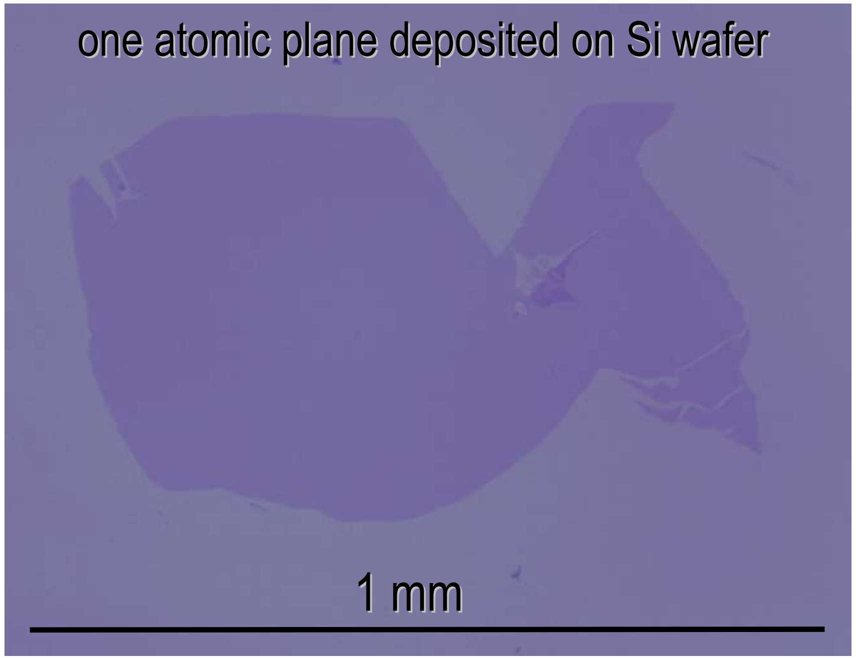


Also: Kurtz 1990; Ebbesen 1995; Ohashi 1997
Ruoff 1999; Kim 2005; McEuen 2005

start with graphite

split into increasingly thinner "pancakes"





until we found a single layer called GRAPHENE

Manchester, *Science* 2004; *PNAS* 2005

1b. MECHANICAL EXTRACTION EN MASSE

split into individual atomic planes

Ruoff, *Nature* 2006
Manchester, *Nanolett '08*
Coleman et al, *Nature Nano '08*

graphene suspension

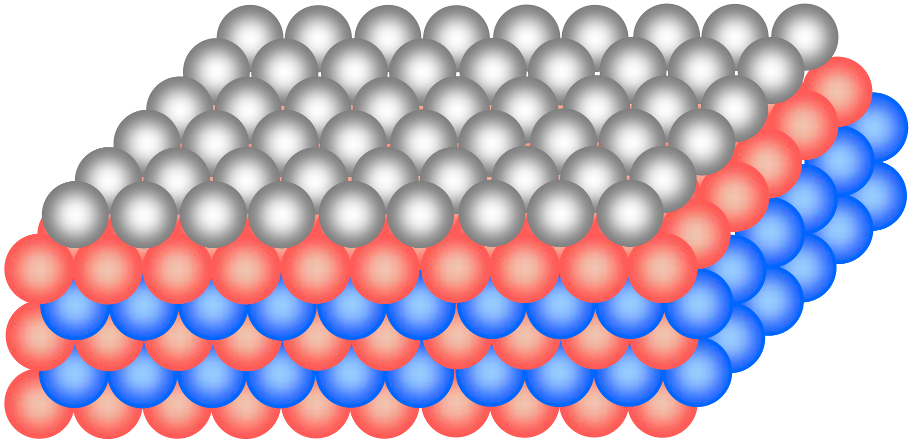
sonication + centrifugation
often intercalation

"powder"

WHEN YOU KNOW THAT
ISOLATED ATOMIC PLANES ARE REALLY INTERESTING

2. CHEMICAL EXTRACTION

epitaxially grown monolayers



chemically remove the substrate

FIRST DEMONSTRATED

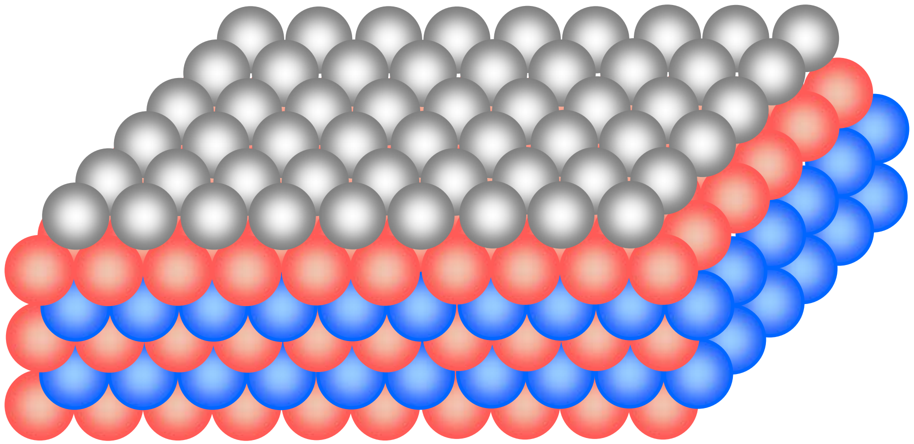
graphene-on-Si wafers

uniform; no multilayer regions;
few cracks; μ >5,000 cm^2/Vs

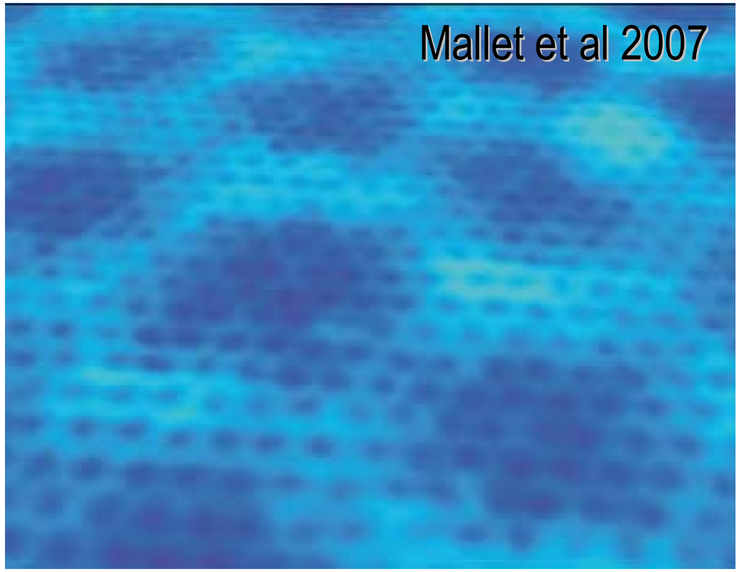
starting idea well before 2004
first suggested, Nature Mat 2007

2b. EXTRACTION ONTO SAME SUBSTRATE

atomic planes decouple during cooling and/or intercalated



special case:
SiC as an insulator



RELATIVELY WEAK INTERACTION
WITH THE GROWTH SUBSTRATE

Bommel 1975; Forbeaux 1998
de Heer 2004; Rotenberg 2006; Seyller 2008

DECOUPLED FURTHER BY PASSIVATION
Starke 2010; Yakimova 2010

MESSAGE TO TAKE AWAY

MATERIALS OF A NEW KIND:
ONE ATOM THICK

atomic planes
were KNOWN before as constituents of 3D systems

now we can *ISOLATE*, *STUDY* and *USE* them
- and mostly importantly - they are worth of it!

WHAT SO SPECIAL ABOUT GRAPHENE?

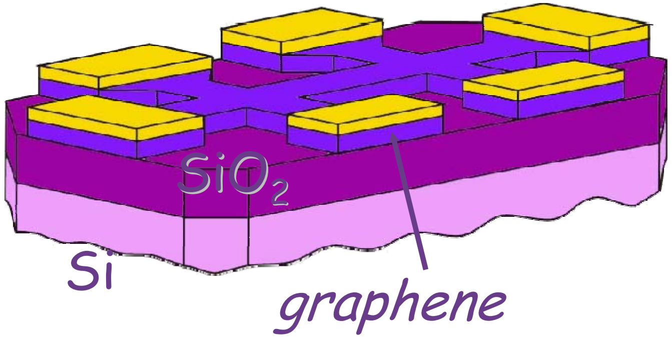
GRAPHENE'S SUPERLATIVES

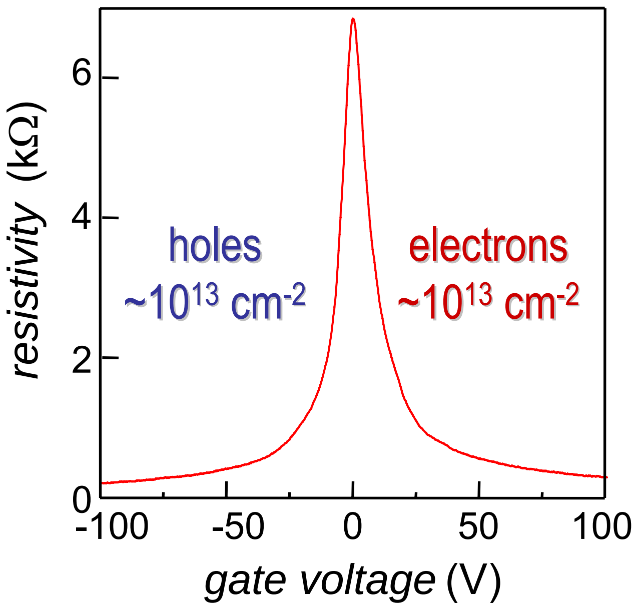
thinnest imaginable material
largest surface area (~2,700 m^2 per gram)
strongest material 'ever measured' (theoretical limit)
stiffest known material (stiffer than diamond)
most stretchable crystal (up to 20% elastically)
record thermal conductivity (outperforming diamond)
highest current density at room T (10^6 times of copper)
completely impermeable (even He atoms cannot squeeze through)
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)

EXCEPTIONAL ELECTRONIC QUALITY & TUNABILITY

AMBIPOLAR ELECTRIC FIELD EFFECT

Manchester, *Science* 2004





carrier mobility at 300K
routinely: ~15,000 $cm^2/V \cdot s$

- CONTROL ELECTRONIC PROPERTIES

homogenous electric doping
from ~10^8 to ~10^{14} cm^{-2}

- ASTONISHING ELECTRONIC QUALITY

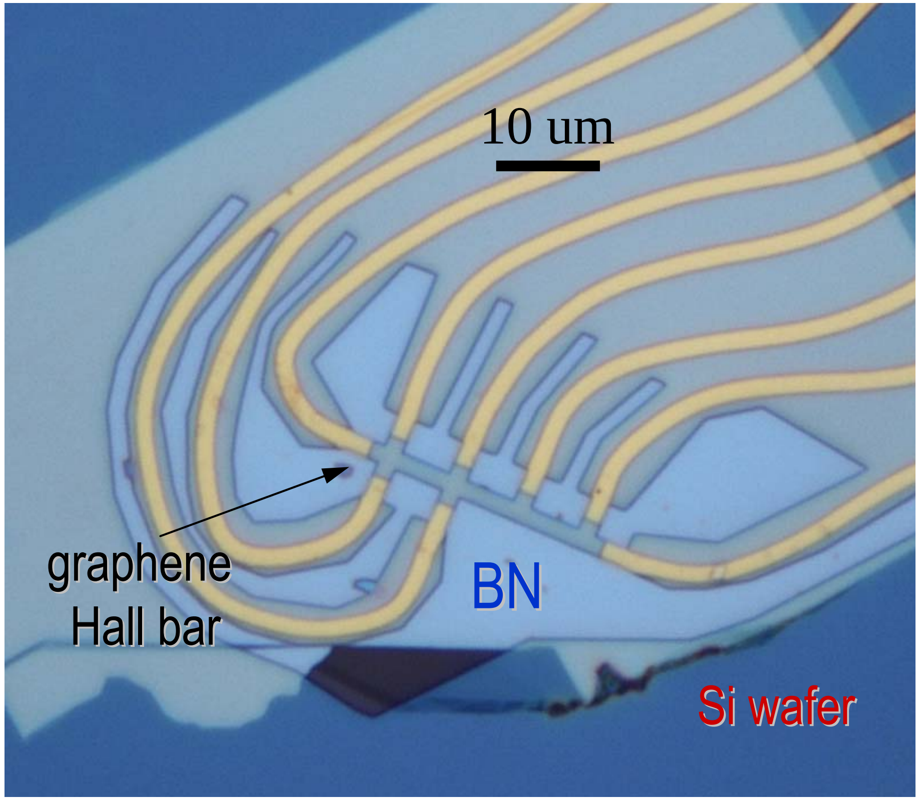
ballistic transport
on submicron scale
under ambient conditions

weak e-ph scattering
POSSIBLE ROOM-*T* MOBILITY
above 200,000 $cm^2/V \cdot s$

Manchester, *PRL* 2008
Fuhrer's group, *Nature Nano* 2008

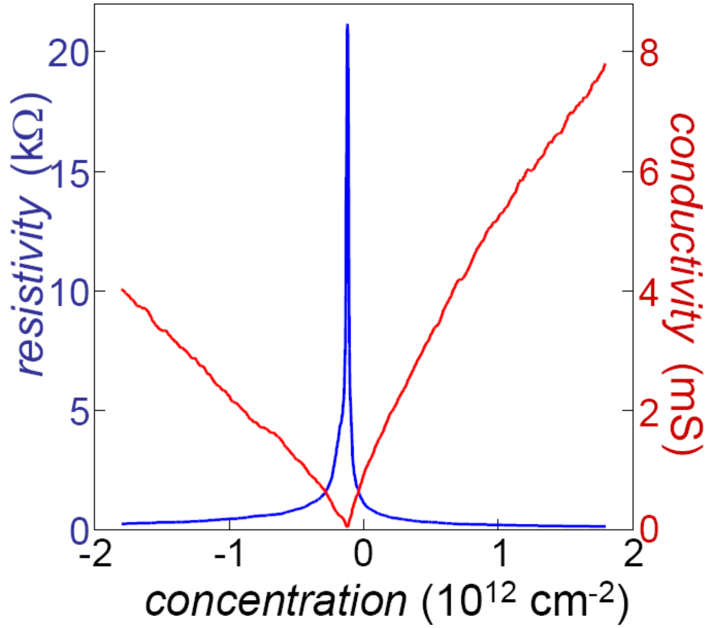
CURRENT STATUS

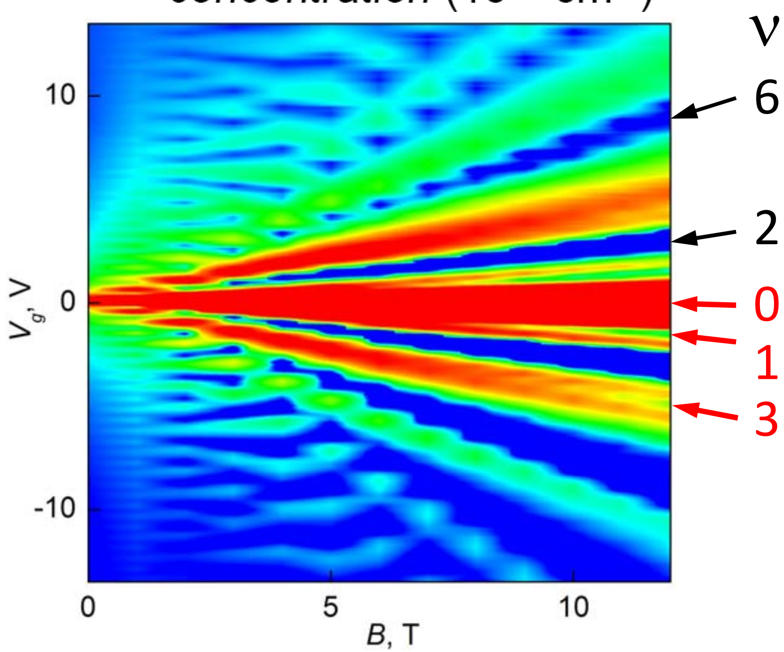
graphene
on atomically flat boron nitride



room-*T* mobility
close to 100,000 cm²/V·s

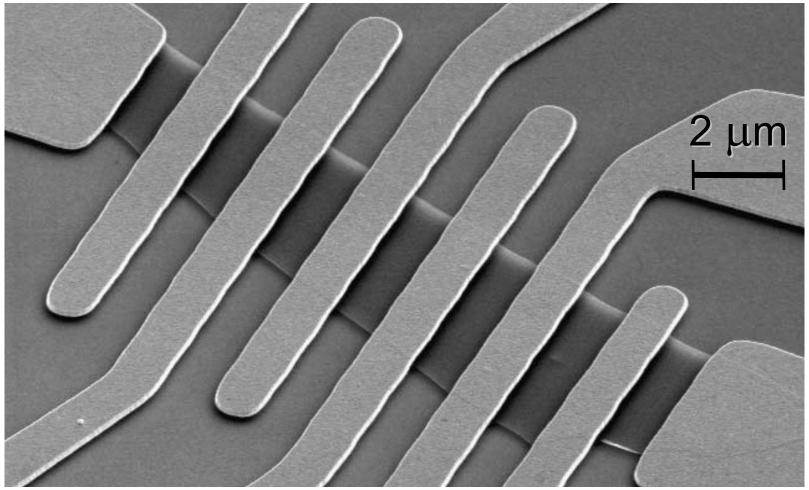
also, Philip Kim's group, *arxiv* 2010





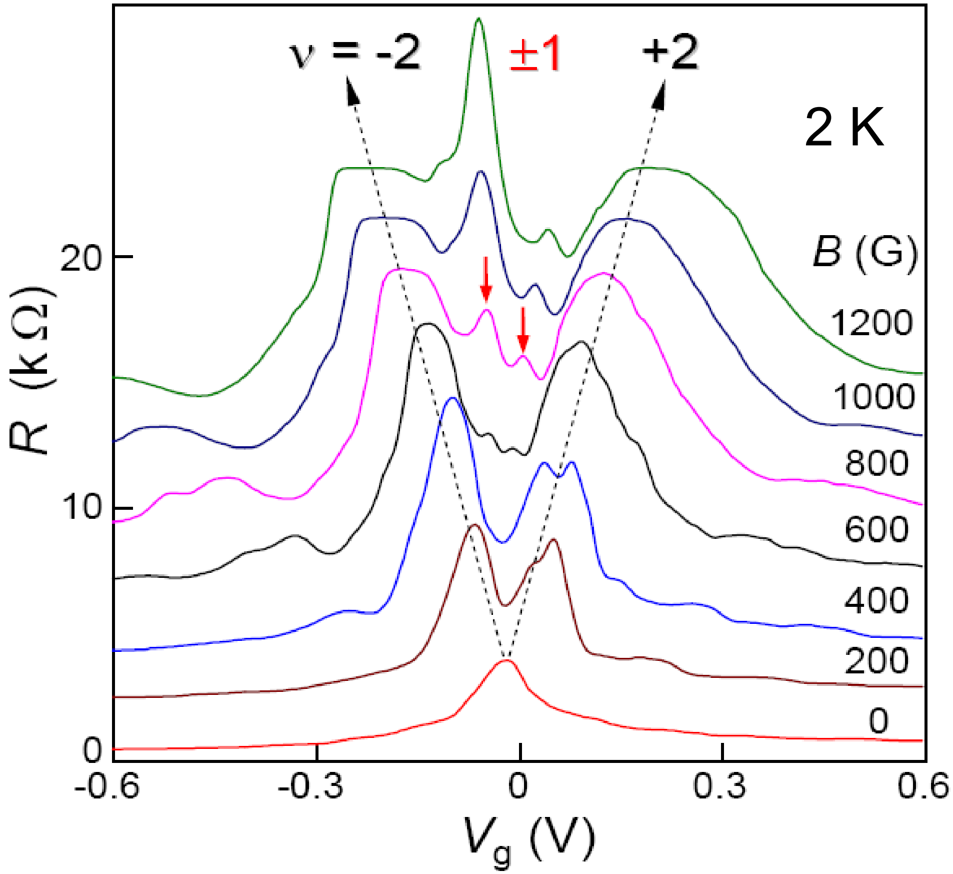
CURRENT STATUS

suspended graphene



2-terminal suspended devices:
first reported by Andrei, Kim & Yacoby
(mobility up to 200,000cm²/V·s)

low-*T* mobilities
few million cm²/V·s
Manchester, arxiv 2010



SdH oscillations start ~50G

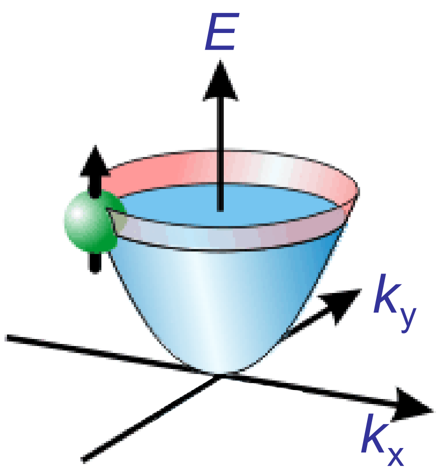
level degeneracy lifted ~ 500G

UNIQUE ELECTRONIC STRUCTURE

VERY SPECIAL ELECTRON WAVES

“Schrödinger fermions”

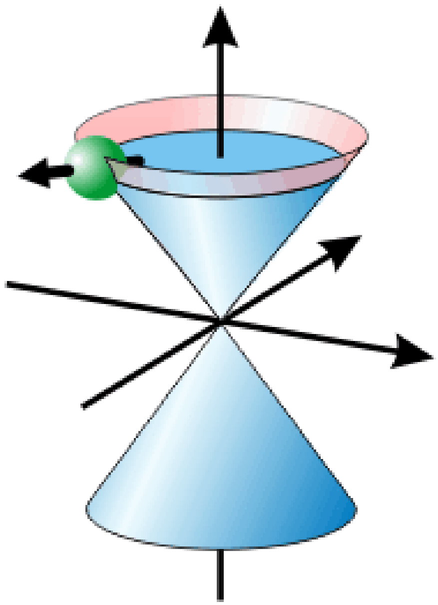
$$\hat{H} = \hat{p}^2 / 2m^*$$



metals
and
semiconductors

ultra-relativistic particles

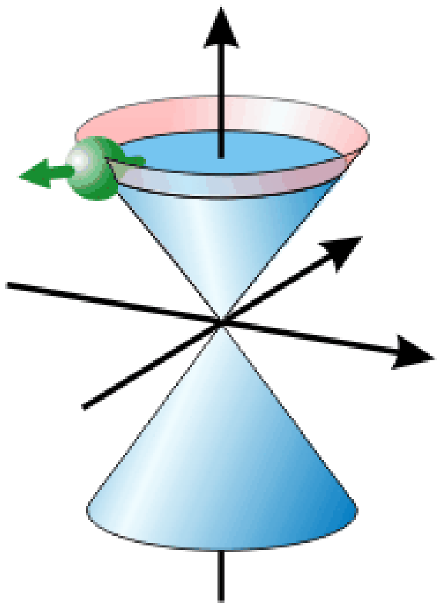
$$\hat{H} = c\,\vec{\sigma} \cdot \hat{p}$$



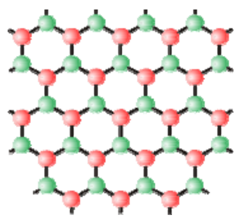
neutron stars
and
accelerators

massless Dirac fermions

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

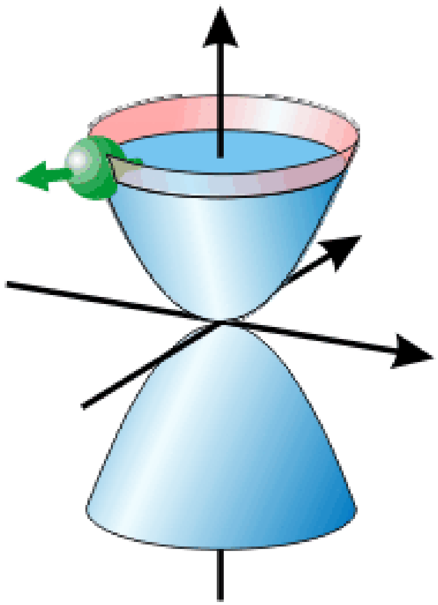


monolayer graphene

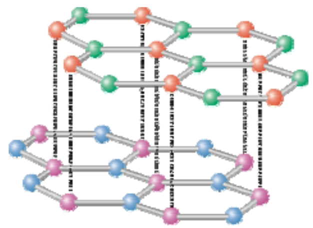


massive chiral fermions

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



bilayer graphene



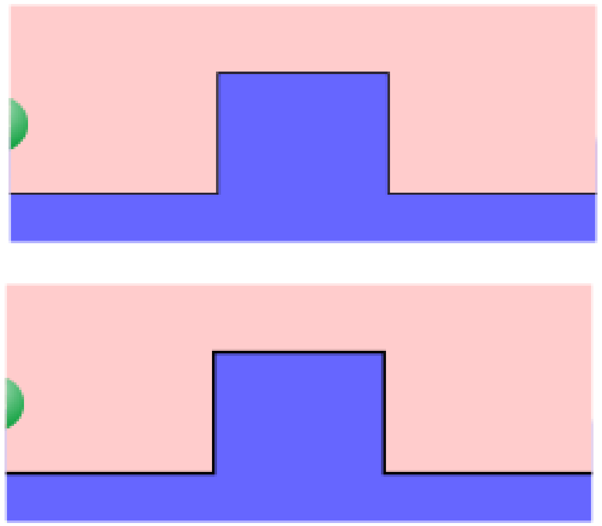
NEW PHYSICS

STUDY OF NEW QUANTUM WORLD

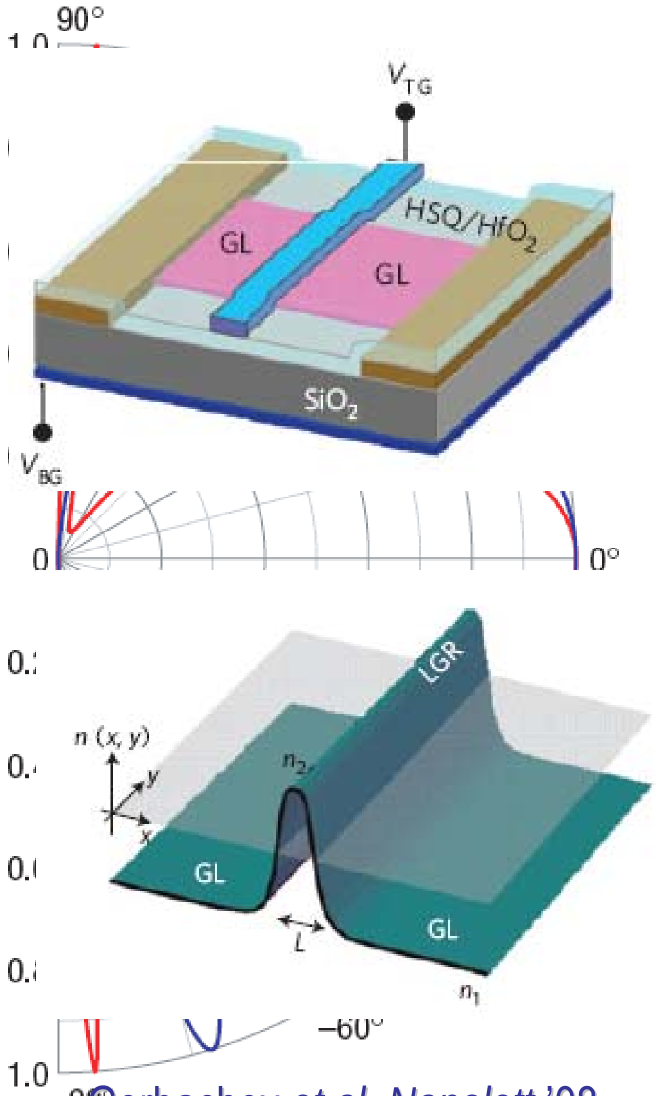
EXAMPLE #1:
"CERN ON A DESK TOP"

Misha Katsnelson, K. Novoselov & AG, *Nature Phys* 2006

Klein Tunnelling



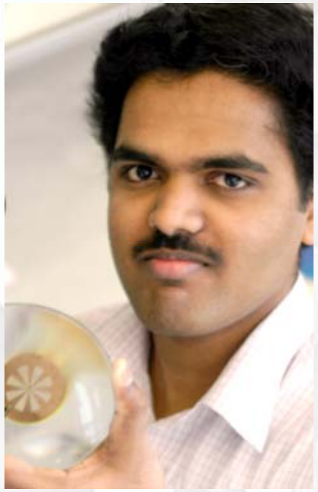
Klein 1929
Katsnelson + Manchester 2006



Gorbachev *et al*, *Nanolett* '08
Stander *et al*, *PRL* '09
Young *et al*, *Nature Phys* '09

EXAMPLE #2:

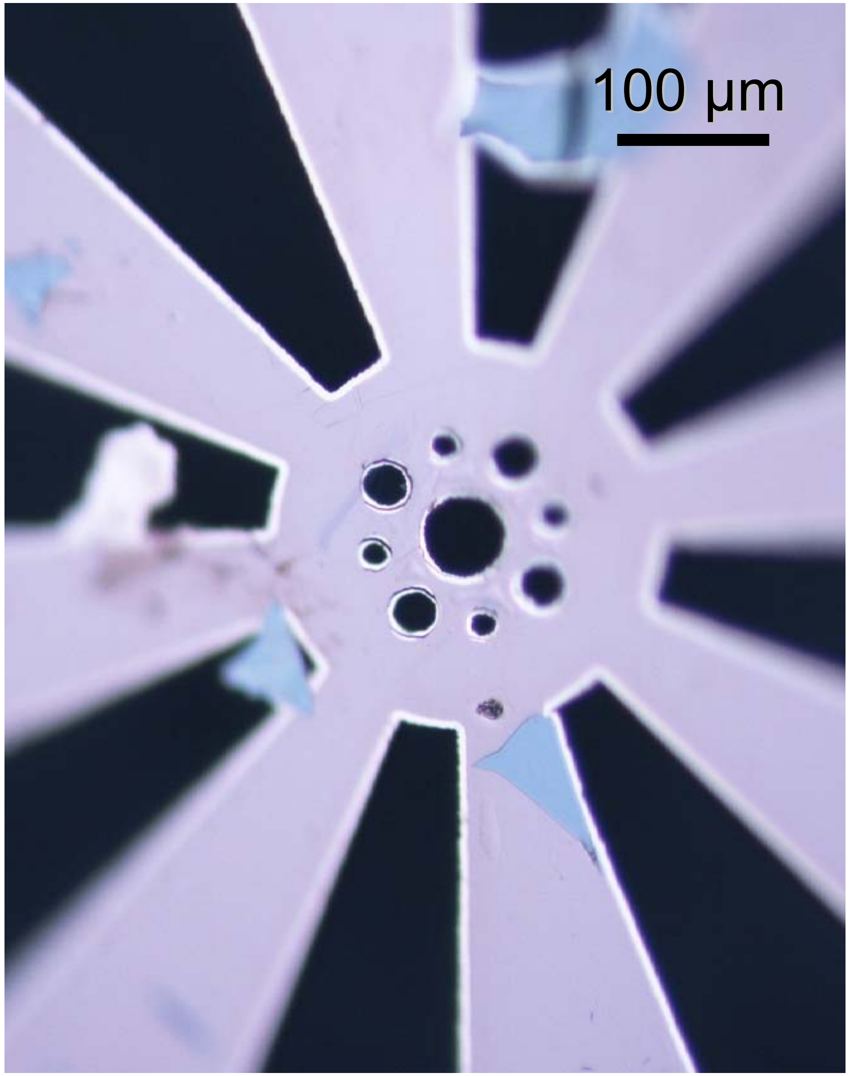
visualization of fine structure constant

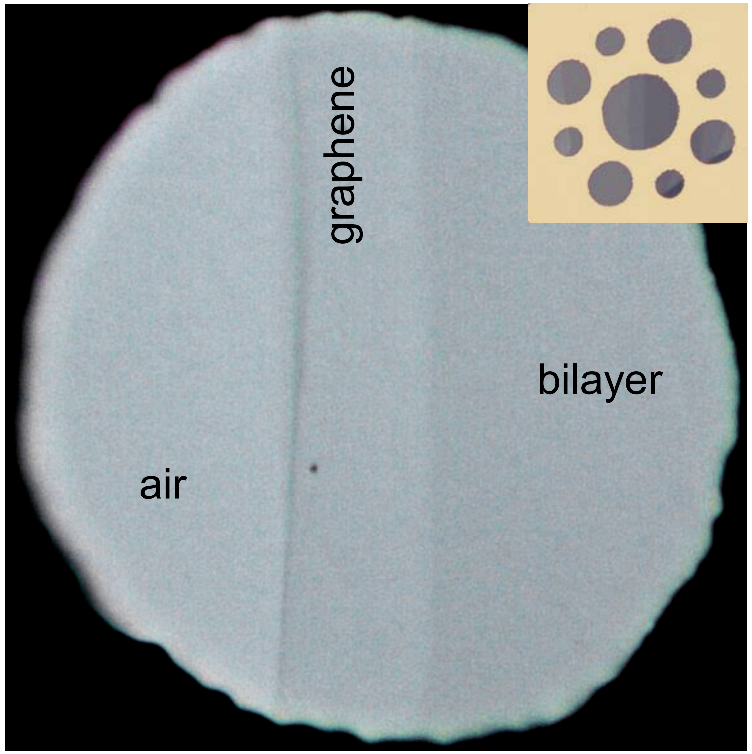


Rahul Nair et al, *Science* 2008

GRAPHENE OPTICS

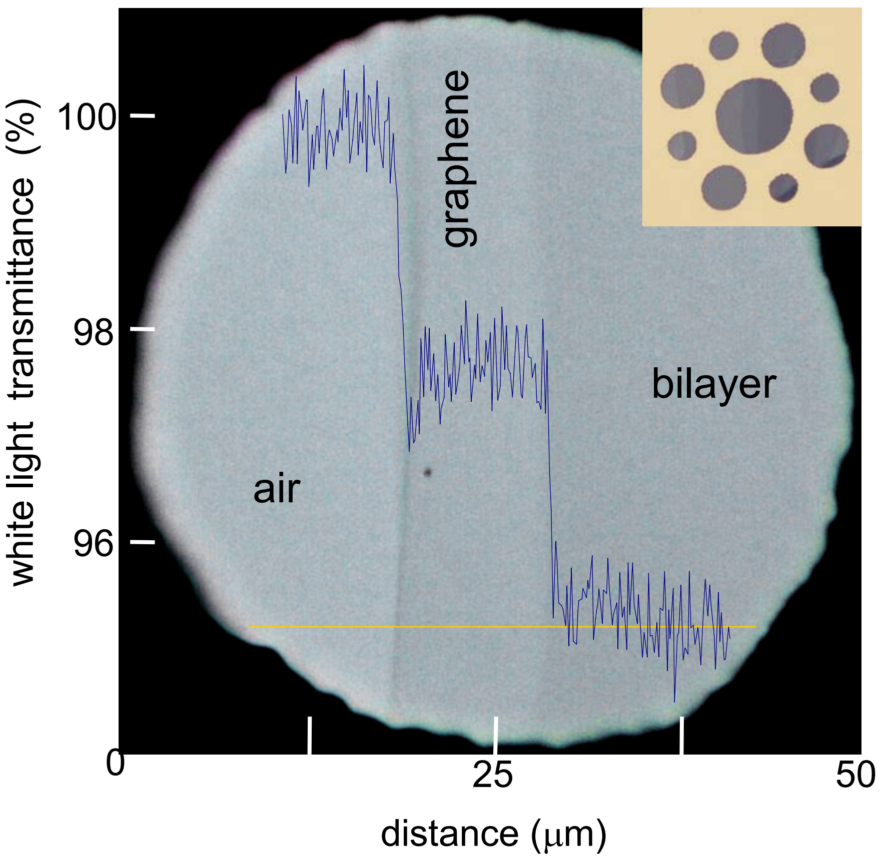
Manchester, *Science* '08



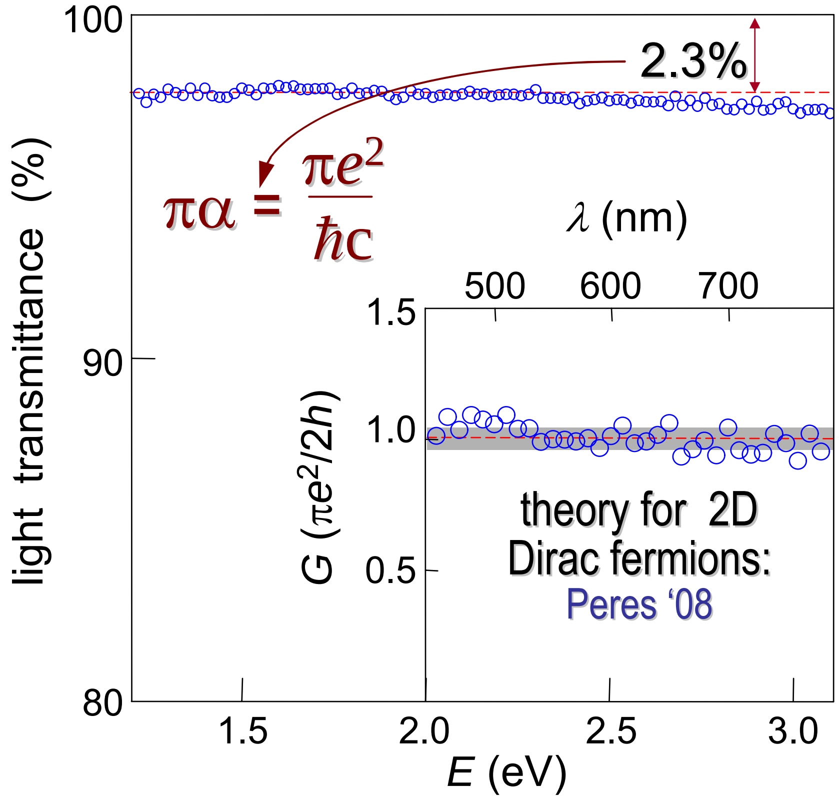


one-atom-thick single crystal
visible by naked eye

GRAPHENE OPTICS



one-atom-thick
single crystal
visible by naked eye



coupling of light with
relativistic-like charges
should be described by
coupling constant α
a.k.a. fine structure constant

EXAMPLE #3

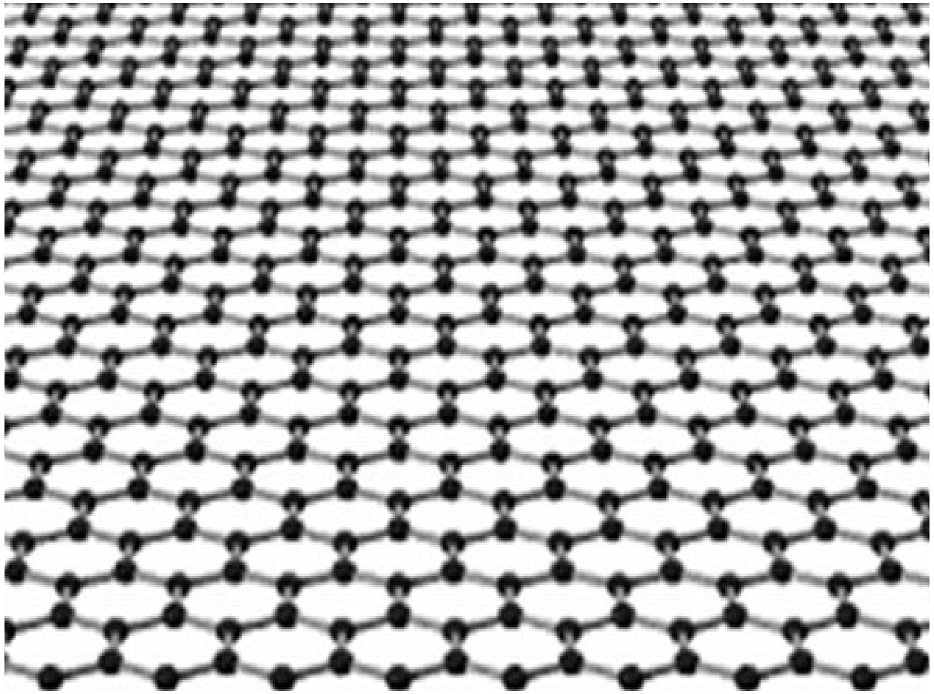
not only Physics:

Chemistry of Individual Giga-Molecules

Kostya Novoselov et al, *Science* 2009&arxiv 2010

Graphene as GigaMolecule

GRAPHENE



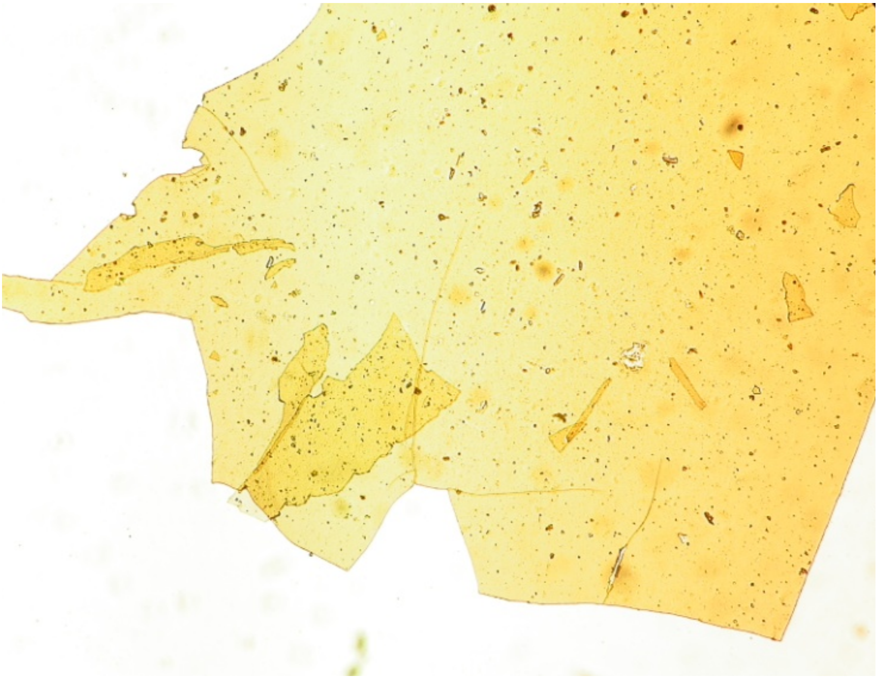
chemical reactions:

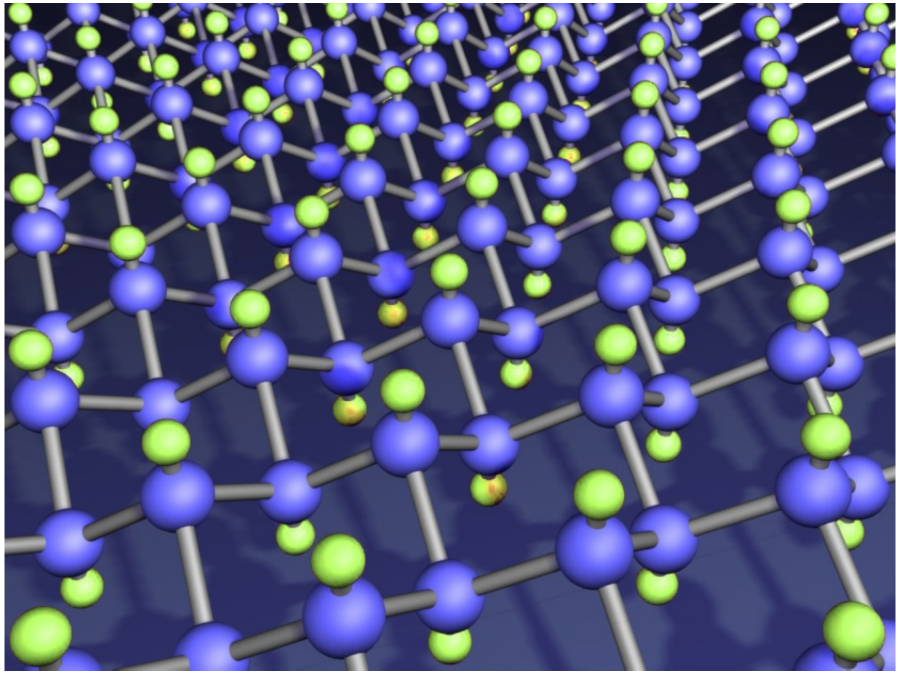
$C^{\infty} + \infty X \Rightarrow CX^{\infty}$

Stoichiometric Derivative

optical gap of ≈3.0eV

fluorographene (*"2D Teflon"*)





chemical reactions:

$C_\infty + \infty F \Rightarrow (CF)_\infty$

exposure to
atomic fluorine, using XeF_2

- *chemically & thermally stable*
  (similar to Teflon)
- *high quality insulator*
- *as strong as graphene*

EXAMPLE #4

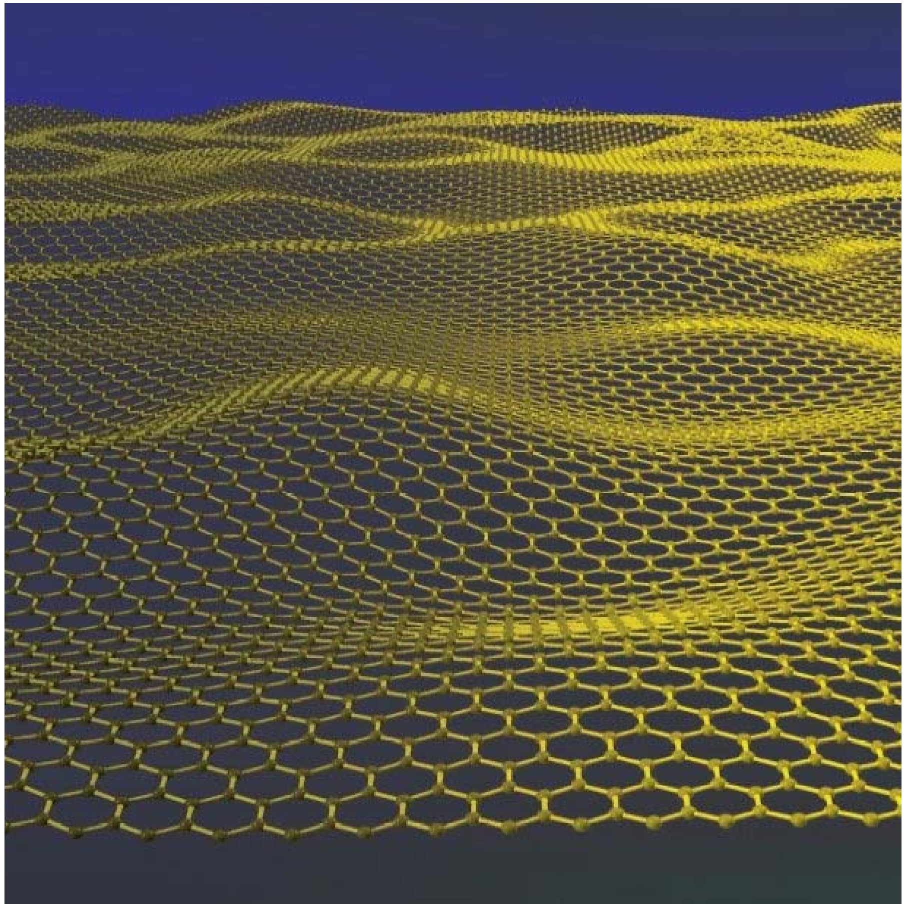
not run out of steam:

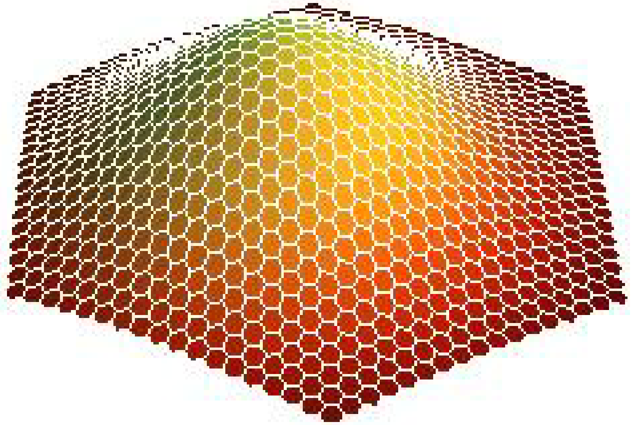
Giant Magnetic Fields by Strain

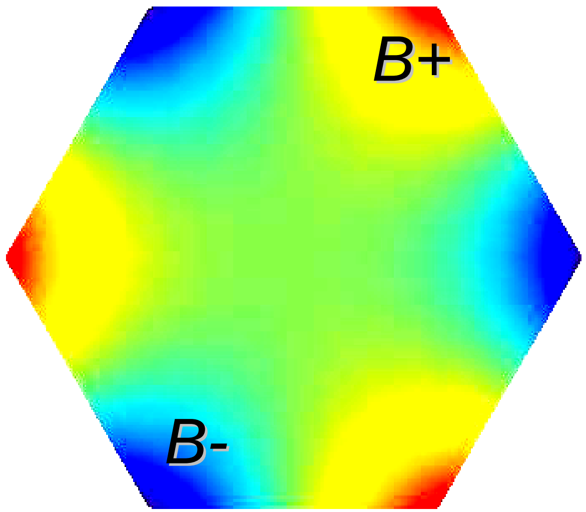
Paco Guinea, M. Katsnelson & AG
Nature Phys 2010

Non-Uniform Strain

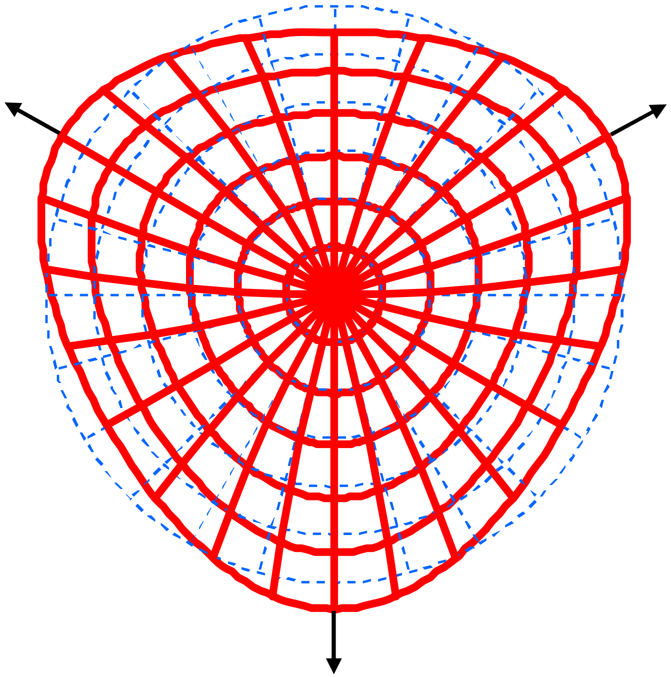
non-uniform strain
causes pseudo-magnetic field
Manchester, *PRL* 2006

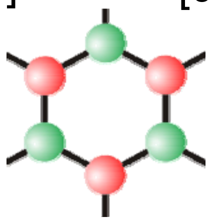


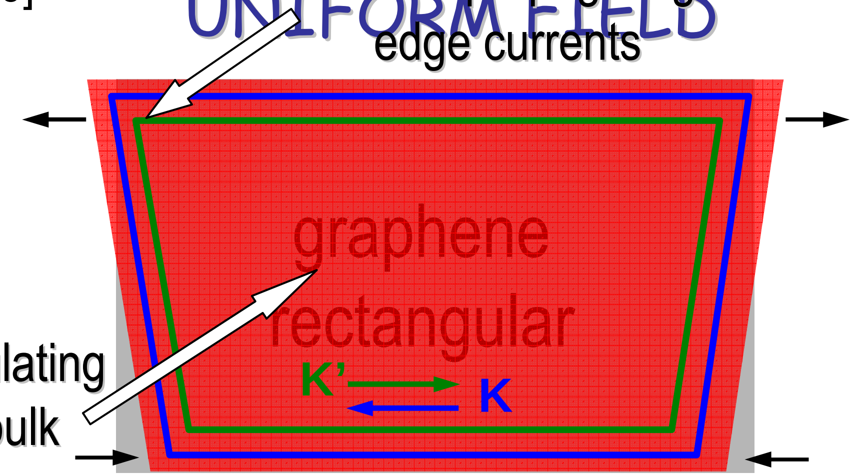




Creating Uniform Pseudo-Magnetic Field

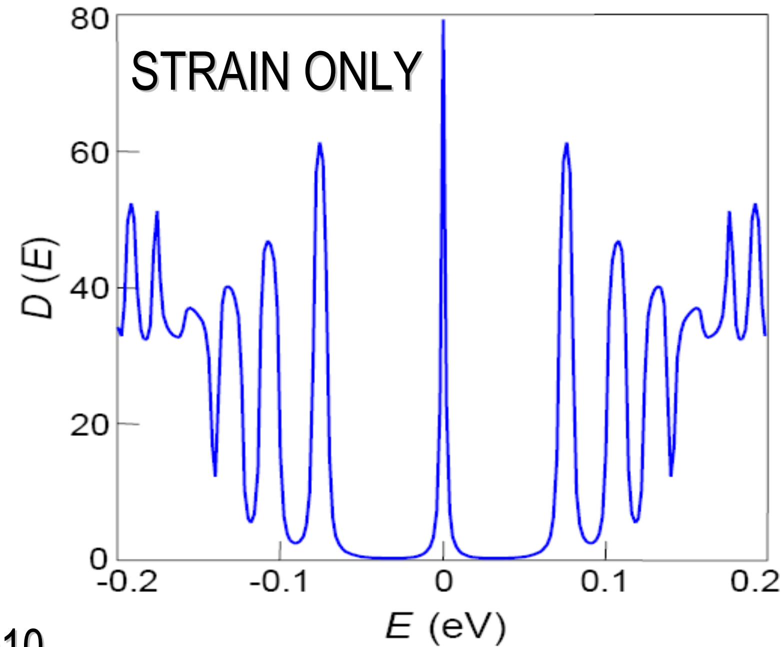






$$B_{\text{eff}} \approx \frac{h}{e} \cdot \frac{\text{strain}}{\text{sample size} \cdot \text{lattice spacing}}$$

field of 10T:
10% strain in μm samples

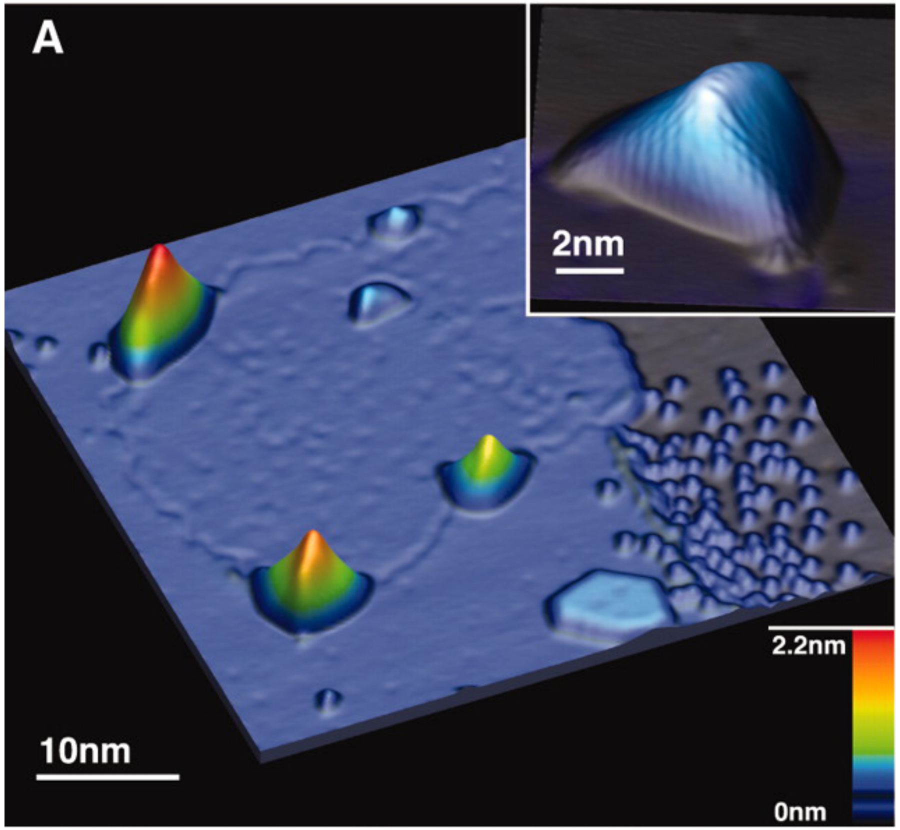


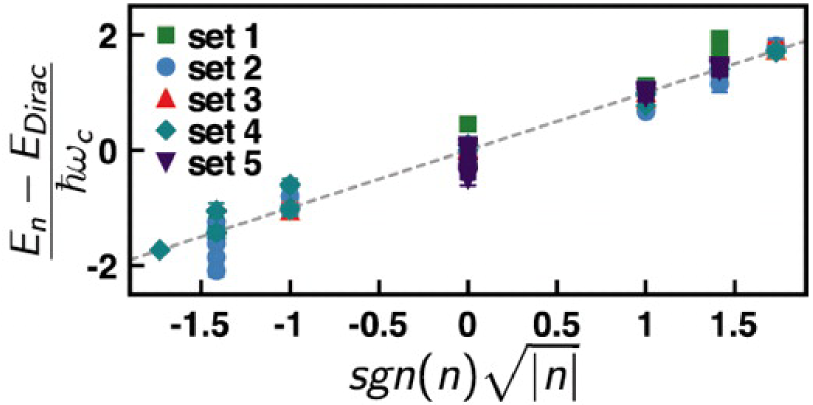
Nature Phys 2010; *PRB* 2010

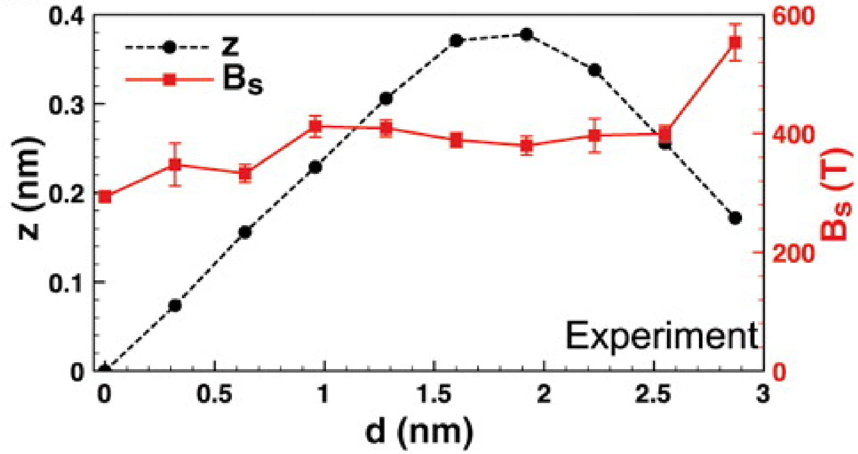
Giant Pseudo-Magnetic Fields

strained graphene bubbles
on Pt surface

M. Crommie's group, *Science* 2010







equivalent to magnetic fields of ~400T

fractional QHE by strain (Bockrath's group arxiv2010)

MESSAGE TO TAKE AWAY

CORNUCOPIA OF NEW SCIENCE

already there

and

very far from being exhausted

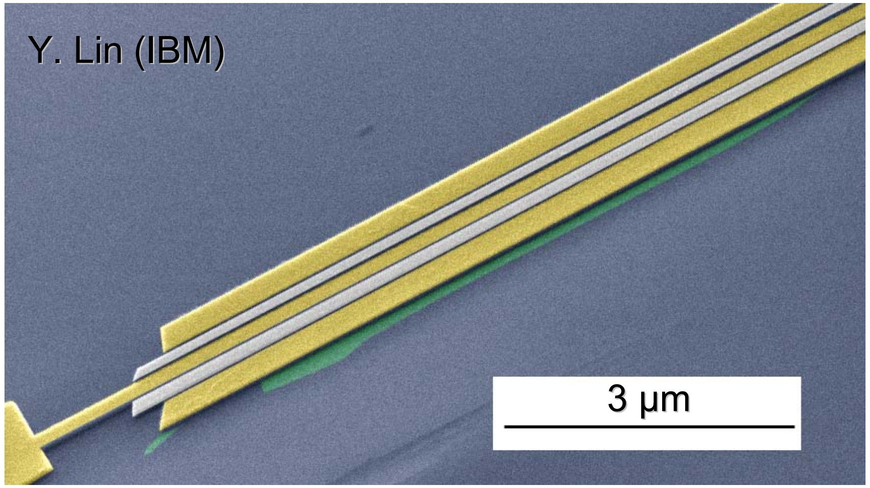
WHAT ABOUT APPLICATIONS?

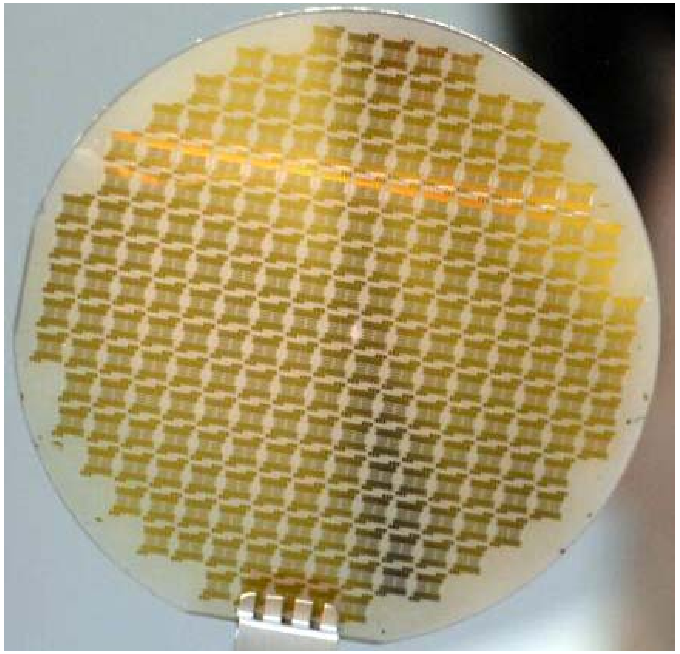
EACH “SUPERLATIVE”
OFFERS SOMETHING NEW & COMPETITIVE

EXAMPLE #1:

Ultra High Frequency Transistors

"BALLISTIC" TRANSISTORS





- ballistic transport
- high velocity
- great electrostatics
- scales to nm sizes

Manchester, *Science* '04

>$30M US military programs:
500 GHz transistors
on sale by 2013 years

2009: 100 GHz (IBM & HRL)

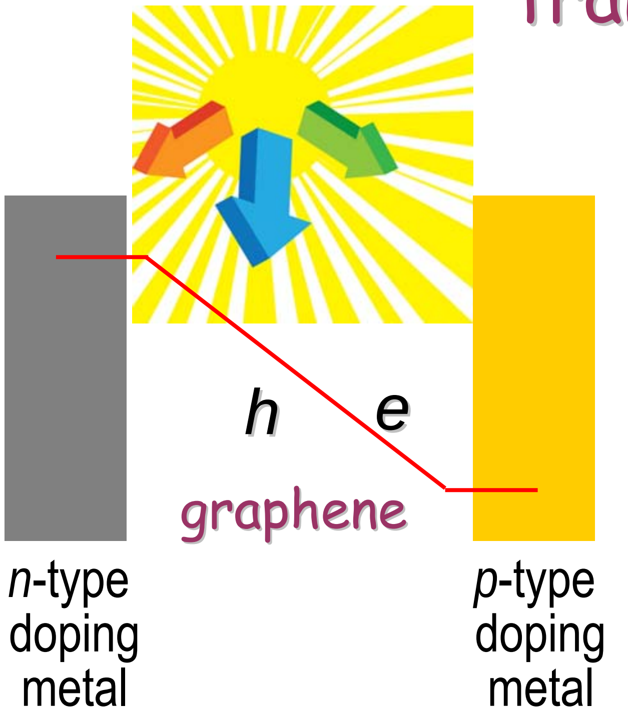
2010: 300 GHz (UCLA & Samsung)
scaling >1THz

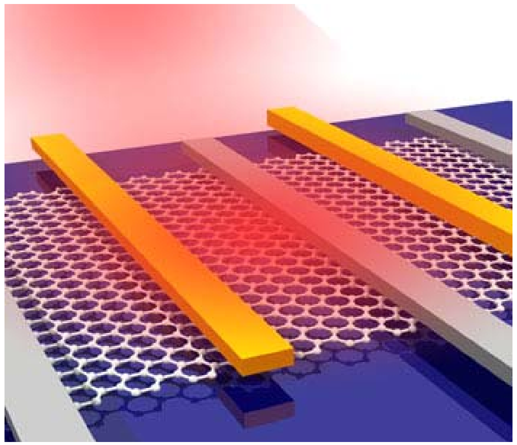
EXAMPLE #2:

OPTOELECTRONICS

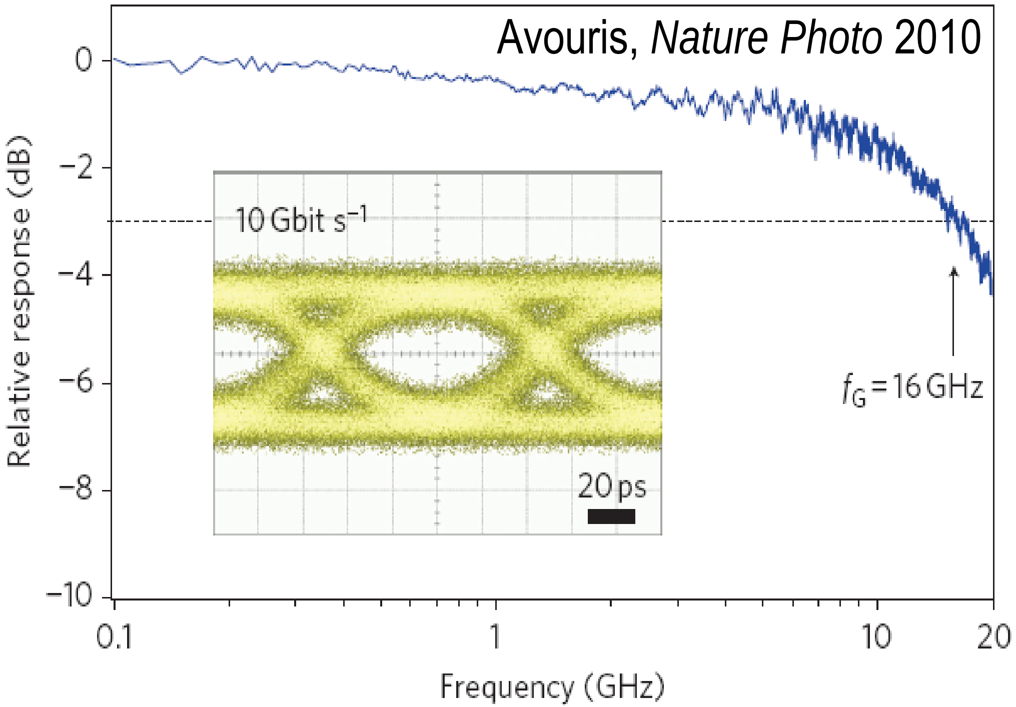
ULTRAFAST PHOTODETECTORS

transparent metal





ballistic transport
of photo-generated carriers
in built-in electric field



EXAMPLE #3:

Graphene instead of ITO

GRAPHENE AS SUBSTITUTE FOR ITO

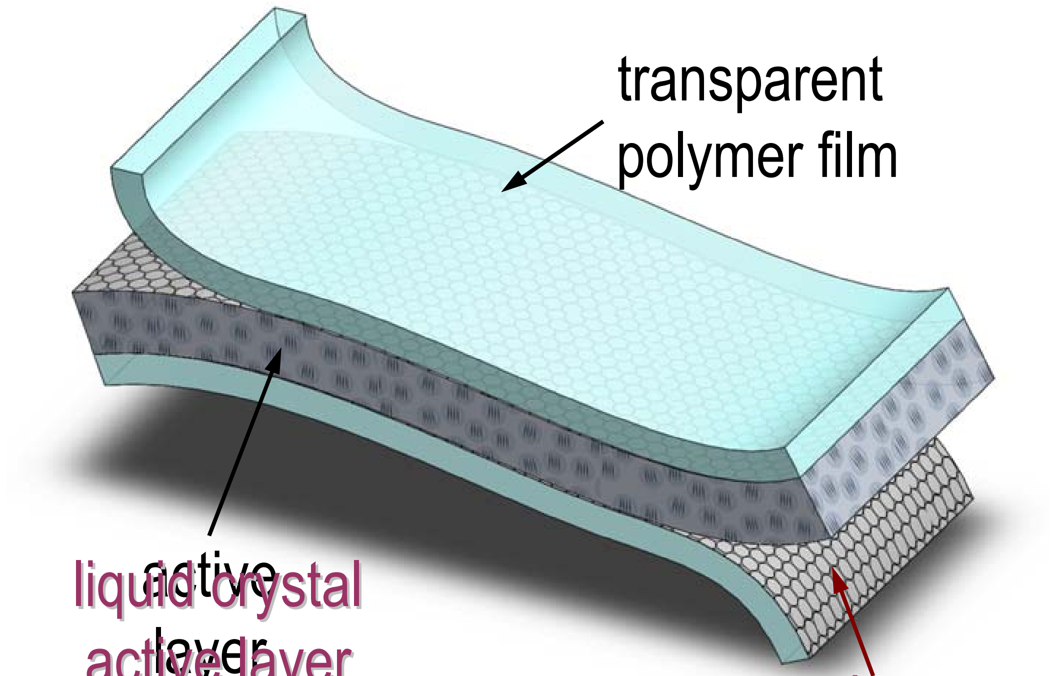
Manchester, *NanoLett* 2008

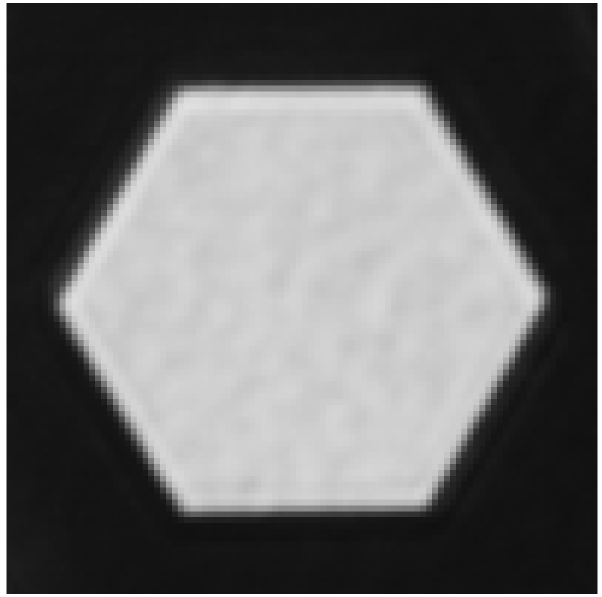
transparent: ~97%

conductive: ρ <100Ω/□

flexible: strain >15%

chemically inert

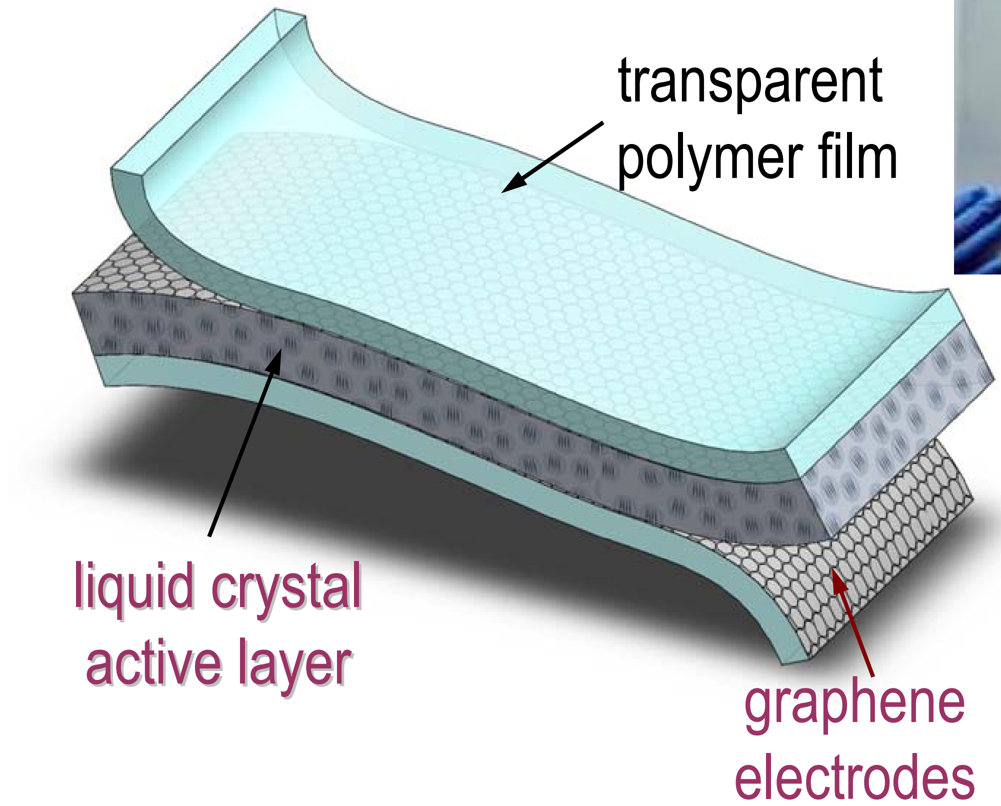


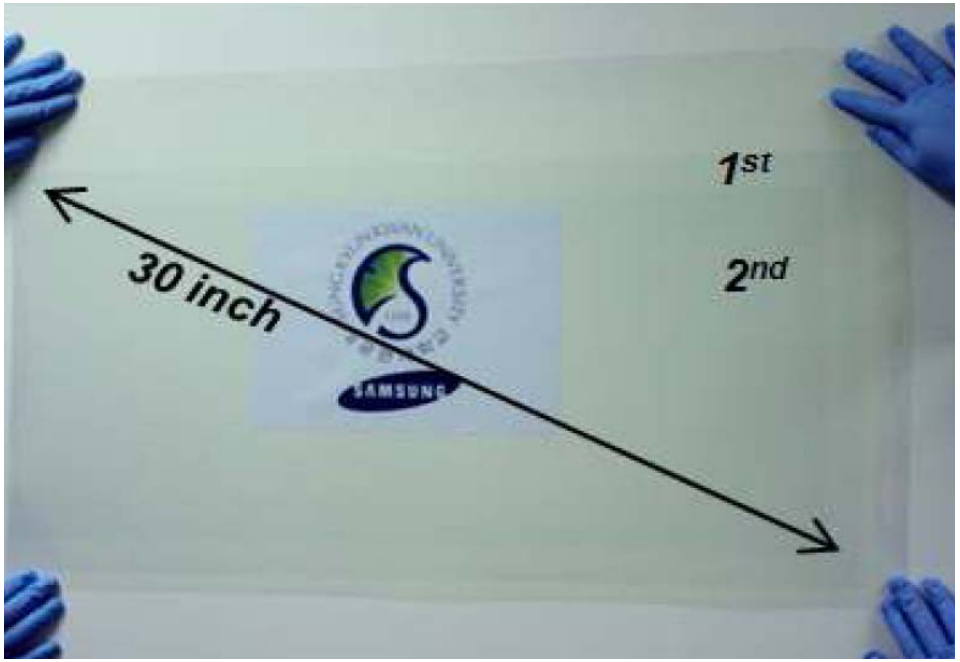


WORKING 10 μm
LCD-GRAPHENE PIXEL

GRAPHENE AS SUBSTITUTE FOR ITO

transparent: ~97%
conductive: ρ <100Ω/□
flexible: strain >15%
chemically inert



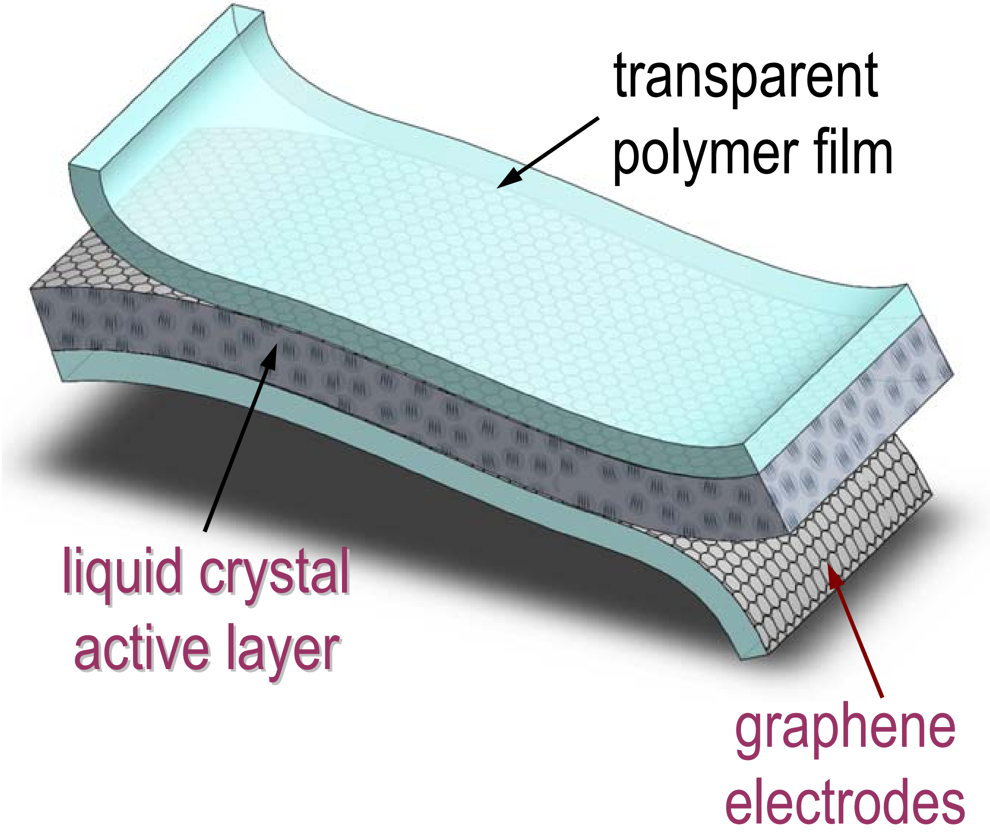


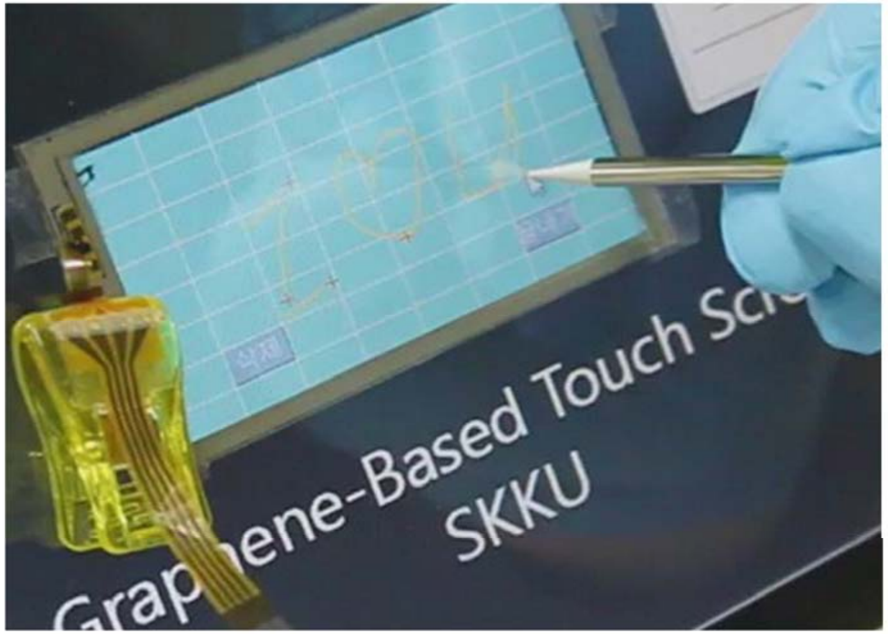
ρ down to 40Ω/□
transparency ~90%
μ ~5,000 cm²/Vs
Hong+Ahn, Nature Nano 2010

reasonably cheap: ~$50/m²

TOUCH SCREENS & OTHERS

bendable & wearable





Samsung's Graphene Road Map:
first products in 2012

Many Other Examples

TEM membranes & conductive ink (on sale)
strain sensors (Samsung's GR map 2014)

…

batteries & supercapacitors
sensors with single-molecule resolution

…

DNA sequencing

…

drilling fluids for oil wells

MESSAGE TO TAKE AWAY

INCREDIBLY RAPID PROGRESS:

AFTER ONLY 5 YEARS
APPLICATIONS
NO LONGER
A WISHFUL THINKING

only their extent remains unclear


Kostya Novoselov


Sergey Morozov (Chernogolovka)

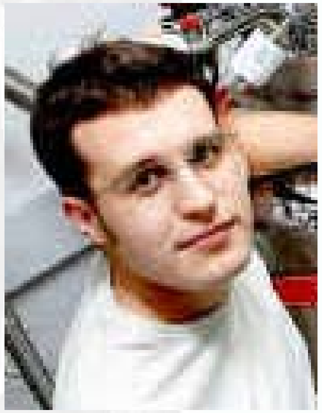

Rahul Nair


Misha Katsnelson (Nijmegen)


Irina Grigorieva


L.Ponomarenko


D. Elias


P. Blake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for graphene reviews, see: Nature Mat '07; RMP '09; Science '09