Graphene: Materials in the Flatland

K.S. Novoselov
thinnest 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)

Graphene: Materials in the Flatland

K.S. Novoselov
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

0d

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

1d

Carbon Nanotube
Multi-wall 1991
Single-wall 1993

2d

Graphene

3d

Graphite
1564
Borrowdale

http://vifslatofsla.livejournal.com/28907.html
http://www.stanford.edu/group/GGG/1D.html
Carbon Allotropes

2d
Graphene

1d
“Buckyball”
Carbon Nanotube

3d
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
Into The Pencil Trace

graphite trace on oxidized Si wafer

first 2D material demonstrated - Manchester, Science '04

~100 layers
Kurtz 1991
Dujardin 1997
Ohashi 1997
Ruoff 1999

0.1 mm

10 to 30 layers
Kim 2005

Manchester 2004

1 µm

1-5 layers Manchester 2004
Into The Pencil Trace

First 2D material demonstrated - Manchester, Science '04

Graphite trace on oxidized Si wafer
Other 2D Crystals

From 3D systems

High Quality
Different From 3D Precursor

Novoselov et al PNAS (2005)

2D bi2Sr2CaCu2Ox in SEM  2D MoS2 in optics

2D boron nitride in optics  2D NbSe2 in AFM
Other 2D Crystals

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

By Chemical Reaction

$C_\infty + \infty H \Rightarrow (CH)_\infty$

FLUOROGRAPHE (graFane)

Manchester Small ‘10

graphane

Manchester Science ‘09
New Class of Crystalline Materials

2-DIMENSIONAL ATOMIC CRYSTALS

Studied (???):
- Graphene

Large Variety of Material Properties
- Boron-Nitride
- Graphane
- Fluorographene

Lightly Touched:
- NbSe$_2$
- MoS$_2$
- MgB$_2$
- BiSCCO

Unexplored:
- Flourographene

...
A Dream: Back From The FLATLAND

Materials on Demand

What kind of properties would this material possess?
2D-Crystals-Based Heterostructures

- MoS$_2$
- Graphene
- Boron-Nitride
- NbSe$_2$
- Graphane
- GraFane
2D-Crystals-Based **Heterostructures**

**New Material:**

**Graphene**
- **ultimately thin**
- **linear gapless spectrum**
- **chemically active**
  - (new materials: graphane, flurographene)

**Bilayer Graphene**
- **two layers – can slide**
- **parabolic gapless spectrum**
  - (chiral massive particles)
  - **GAP CAN BE OPENED**
- **chemically less active**

**Graphite**
- **cleaves easily**
- **semimetal**
  - chemically less active

Kuzmenko et al, PRB (2009)
Young et al arXiv:1004.5556v2
2D-Crystals-Based Heterostructures

Weak Coupling (Coulomb interaction)

Strong Coupling (tunnelling regime)

Coulomb Drag
Three Key-Points

Unusual Electronic Properties
New Types of Quasiparticles

“Schrödinger fermions”
\[ \hat{H} = \frac{\hat{p}^2}{2m^*} \]

Electron metal

Hole metal

massless Dirac fermions
\[ \hat{H} = v_F \vec{\sigma} \cdot \hat{p} \]
Semenoff 1984

massive chiral fermions
\[ \hat{H} = \vec{\sigma} \cdot \hat{p}^2 / 2m^* \]
Falko 2006

monolayer graphene
neutron stars & accelerators

bilayer graphene
Graphene Field Effect Transistors

carrier mobility currently: up to ~50,000 cm²/V·s at 300K even when strongly doped

~1,000,000 cm²/V·s at 4K (Andrei, Kim & Manchester group)

intrinsic (phonon-limited): >200,000 cm²/V·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)
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 1.500cm²/V·s

Graphene Quantum Dots
and Single Electron Transistors

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
the fine structure constant observed “with a naked eye”
\[ \alpha = 1/137 \pm 2\% \]

\[ \pi \alpha = 3.14.. \times 1/137 \]

Do it at home
Graphene-based Liquid Crystal Display

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
- 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)
- ... ...


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

Direct transfer on any surface

Release graphene by etching Ni

fish by TEM grid

remove PMMA

Graphene SiO$_2$
First Graphene Products are Already There

Support for Biomolecules in TEM:

UltraStrong
UltraThin
Crystalline

Tobacco Mosaic Virus on graphene
Manchester 2010
Mass Production of Graphene

CVD growth & transfer are well developed

\[ \rho \sim 40 \, \Omega/\square \quad \text{transparency} \sim 90\% \]

\[ \mu \sim 5,000 \, \text{cm}^2/\text{Vs} \]

All Major Applications are Realistic

**Photovoltaics**
(Samsung roadmap: 2012)

- **Photodetectors**
- **Electronics**
  - **RF Transistor**
- **Composite Materials**
  - Mechanically Strong; Conductive; Optically Active

**Touch-screens**

**Solar Cells**

- **Liquid Crystal Display (LCD)**
- **Gas Sensor**
- **Strain Gauge**
- **Variable Capacitor**

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