An Experimental Tour Through
Some of the Unique Properties of Graphene

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What is Graphene?

Conjugated structures of Carbon atoms

0D
Fullerenes

1D
Nanotubes

2D
Graphene

Carbon Electronics
Up to mm size exfoliated graphene
Seeing one-atom layers one at a time
A simple tight-binding

Two inequivalent C atoms

\[ H = t \sum_{i,j} \left( A_{\vec{R}_i} A_{\vec{R}_j} + B_{\vec{R}_j} B_{\vec{R}_i} \right) \]

Solutions are plane waves

\[ |\psi_k\rangle = \left( \alpha_k \sum_i e^{ik\vec{R}_i} A_{\vec{R}_i}^\dagger + \beta_k \sum_j e^{ik\vec{R}_j} B_{\vec{R}_j}^\dagger \right) |0\rangle \]

OR

\[ |\psi_k\rangle = \sum_i e^{ik\vec{R}_i} \begin{pmatrix} \alpha_k A_{\vec{R}_i}^\dagger \\ \beta_k B_{\vec{R}_j}^\dagger \end{pmatrix} |0\rangle \]

pseudo spin
2D Dirac Massless Electrons in Graphene

\[ \hbar v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} \begin{pmatrix} \alpha_k \\ \beta_k \end{pmatrix} = E(k) \begin{pmatrix} \alpha_k \\ \beta_k \end{pmatrix} \]

\[ \vec{q} = \vec{K} + \vec{k} \]

Linear dispersion relation

Semimetal

Two atoms in unit cell

Two K-points

Zero mass

Zero-gap semiconductor

Pseudo-spin + Chiral electrons

New quantum numbers
Graphene Transistors

Novoselov/Geim 2004

Graphene
First generation

Silicon
Integrated circuits

\[ \rho \sim 10,000 \text{ cm}^2/\text{Vs} \]

\[ \rho \sim 1,000 \text{ cm}^2/\text{Vs} \]
Quantum Hall effect of Dirac fermions

Novoselov/Geim; Kim – November 2005
Quantum Dynamics of Electrons

Schrödinger: Non-relativistic

\[ -\frac{\hbar^2}{2m} \Delta + V(\vec{r}) \psi = E\psi \]

Dirac: Relativistic

\[ \left( \gamma^\mu \frac{\partial}{\partial x^\mu} + \frac{mc}{\hbar} \right) \psi = 0 \]

Ex.: Integrated Electronics

High-Energy Particle Physics
Large area graphene - CVD

Heat Methane at 1000 C

Polymer layer to support graphene

On Copper substrate:
Methane decomposes
Graphene grows

Remove Copper: wet etching

Final step:
Transfer Graphene

Ruoff/Kong/Samsung 2009
Process is robust: after ~ 6 months of lab scale work
Produce by the meter – sell by the inch

Roll-to-roll synthesis of graphene
Ease of access + Gate tuning

Superconducting electronics

Spintronics

Van Wees 2007
Single Molecule Detection

1 molecule donates/ remove 1 electron

Detect change of resistivity

Novoselov/Geim 2007
1, 2, 3... More is different

Linear

Parabolic

Small Band overlap
Tunable band structure

Ex.: Silicon band structure

Band structure of conventional Semiconductors

Fixed once you pick a material!

Band structure of few-layer graphene can be tuned using gates
Double gating

**Top gate**

**Bottom gate**

**Single layer**

**Double layer**

Band-gap opening in nano-electronic devices
Turning bilayers into insulators

Chiral particles with quadratic dispersion

\[ H = \alpha \begin{pmatrix} \Delta & (k_x - ik_y)^2 \\ (k_x + ik_y)^2 & -\Delta \end{pmatrix} \]
Topological confinement

Lateral confinement in Bilayer graphene

“Normal” confinement

“Topological” confinement

Chiral zero modes

Gate electrode
Gate insulator

Martin, Blanter, Morpurgo 2008
Topology in k-space

\[ H = \begin{pmatrix} \Delta & (k_x - ik_y)^2 \\ (k_x + ik_y)^2 & -\Delta \end{pmatrix} = -g(k) \cdot \sigma \]

With J. Li, M. Büttiker, I. Martin 2010

General expression for topological invariant

\[ N = \frac{e \mu \nu \lambda}{24 \pi^2} \text{Tr} \int d^2k d k_0 G \partial_{k_\mu} G^{-1} G \partial_{k_\nu} G^{-1} G \partial_{k_\lambda} G^{-1} \]

For 2 x 2 case

Hall conductance

\[ \sigma_H = N = \frac{1}{4\pi} \int d^2k \hat{g} \cdot (\partial_{k_x} \hat{g} \times \partial_{k_y} \hat{g}) \]

\[ \hat{g}(k) \] texture on one side of kink

Number of zero-modes is topologically protected
Ex.: Gate tunable light source

Gallium Arsenide

Tunable light sources
from THz to far infrared

Frequency fixed by gap $\Delta$
$\Delta = h\nu$

Graphene bilayer=
Tunable gap
Trilayer: the opposite effect

Each « layer sequence » is a different material
Cleaning graphene

Observing the interactions between Dirac electrons

Exploring new substrates

Lau 2012

Kim 2010
Few atom thick crystals

High-quality transistor action in metal dichalcogenides
Kis 2011

Gate-induced superconductivity in ZrNCl
Iwasa 2010

Surface states in topological insulators
AM 2011
Nuclear Magnetic Resonance Imaging

1944: for his resonance method for recording the magnetic properties of atomic nuclei

1952: for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith

1977: First MRI scan on humans

Today
2000: for the discovery and development of conductive polymers

1985: First semiconductor devices (OLEDs, Solar cells)

~1975

Today:

OLED TV

Flexible screens

Organic Conductors and Semiconductors

H.J. Heeger  A.G. MacDiarmid  H. Shirakawa
Graphene

2010: for groundbreaking experiments regarding the two-dimensional material graphene

Already demonstrated today
- Transparent electrodes
- Molecular sensors
- High-frequency switches
- Optical sources
- Composite materials
- Photonic devices
- ...

Tomorrow?