Antonio H. Castro Neto

Funding by:

The carbon new age
Diamond

Graphite
Fullerenes or Buckyballs
zero dimensional

C20

C60

C540
Fullerenes or Buckyballs
zero dimensional

C20

C60

C540
Fullerenes or Buckyballs
zero dimensional

C20

C60

C540
Fullerenes or Buckyballs
zero dimensional

C20

C60

C540

Fullerenes or Buckyballs
zero dimensional
The making of a fullerene
1. Take graphene
2. Add a pentagon
3. Add a few more!
3. Add a few more!
Carbon Nanotubes: one dimensional
Carbon Nanotubes: one dimensional
Beautiful… and useful!
Beautiful... and useful!

Microscopic electric cables
Nanomechanical Resonators
Chemical sensors
Graphite
Graphite
Stacked graphene!
Drawing conclusions from graphene
Drawing conclusions from graphene
Drawing conclusions from graphene

5 \mu m
Drawing conclusions from graphene

Graphene has been produced since the pencil was invented in England in 1564!
Electric Field Effect in Atomically Thin Carbon Films


We describe monocrystalline graphitic films, which are a few atoms thick but are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films are found to be a two-dimensional semimetal with a tiny overlap between valence and conductance bands, and they exhibit a strong ambipolar electric field effect: such that electrons and holes in concentrations up to $10^{13}$ per square centimeter and with room-temperature mobilities of $\sim 10,000$ square centimeters per volt-second can be induced by applying gate voltage. The ability to control electronic properties of a material by externally applied voltage is at the heart of modern electronics. In many cases, it is the electric field effect that allows one to vary the carrier concentration in a semiconductor device and, consequently, change an electric current through it. As the semiconductor industry is nearing the limits of performance improvements for the current technologies dominated by silicon, there is a constant search for new, nontraditional materials whose properties can be controlled by the electric field. The most notable recent examples of such materials are organic conductors (1) and carbon nanotubes (2). It has long been tempting to extend the use of the field effect to metals [e.g., to develop all-metallic transistors that could be scaled down to much smaller sizes and would consume less energy and operate at higher frequencies than traditional semiconducting devices (3)]. However, this would require atomically thin metal films, because the electric field is screened at extremely short distances (<1 nm) and bulk carrier concentrations in metals are large compared to the surface charge that can be induced by the field effect. Films so thin tend to be thermodynamically unstable, becoming discontinuous at thicknesses of several nanometers; so far, this has proved to be an unsurmountable obstacle to metallic electronics, and no metal or semimetal has been shown to exhibit any notable (>1%) field effect (4).

We report the observation of the electric field effect in a naturally occurring two-dimensional (2D) material referred to as few-layer graphene (FLG). Graphene is the name given to a single layer of carbon atoms densely packed into a benzene-ring structure, and is widely used to describe properties of many carbon-based materials, including graphite, large fullerenes, nanotubes, etc. (e.g., carbon nanotubes are usually thought of as graphene sheets rolled up into nanometer-sized cylinders) (5–7). Planar graphene itself has been presumed not to exist in the free state, being unstable with respect to the formation of curved structures such as soot, fullerenes, and nanotubes (5–14).
Recipe for making a graphene transistor
Recipe for making a graphene transistor

Graphite Flakes (Kish, Toshiba Ceramics)

Graphite Flake

Peeling a Graphite Flake

Cleaving to a SiO₂/Si wafer

Gentle Rubbing with plastic Tweezers

Removing the Scotch Tape
Plus some nanotechnology…

- optical image
Plus some nanotechnology…

- optical image
- SEM image
Plus some nanotechnology…

- optical image
- SEM image
- design
Plus some nanotechnology…

- optical image
- SEM image
- design
- contacts and mesa
Exfoliation
Exfoliation

Growth on SiC

Growth on SiC


Exfoliation

Growth by CVD

Exfoliation

Growth on SiC

Growth by CVD

Exfoliation

Growth on SiC


Growth by CVD

Kim et al., Nature 457, 706-710 (2009)
What is so special about graphene?
What is so special about graphene?

Normal conductor
What is so special about graphene?

Normal conductor  Fermions

\[ E(p) = \frac{p^2}{2m} \]
What is so special about graphene?

Normal conductor

Fermions

Graphene

\[ E(p) = \frac{p^2}{2m} \]
What is so special about graphene?

Normal conductor

Fermions

Graphene

Dirac fermions

$E(p) = \pm \nu p$

$E(p) = \frac{p^2}{2m}$
What is so special about graphene?

Normal conductor

Fermions

Graphene

Dirac fermions

$E(p) = \frac{p^2}{2m}$

But how...?
The electronic properties of graphene

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F. Guinea
Instituto de Ciencia de Materiales de Madrid, CSIC, Cantoblanco, E-28049 Madrid, Spain

N. M. R. Peres
Center of Physics and Department of Physics, Universidade do Minho, P-4710-057, Braga, Portugal

K. S. Novoselov and A. K. Geim
Department of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, United Kingdom

(Published 14 January 2009)
Origin of Dirac fermions in graphene

Benzene molecule

$p_z$ states

$\pi$ state

$t \sim 2.7 \text{ eV}$
Origin of Dirac fermions in graphene
Origin of Dirac fermions in graphene

Unit cell
Origin of Dirac fermions in graphene

Unit cell

Nearest neighbors

t ~ 2.7 eV
Origin of Dirac fermions in graphene

$\mathbf{t'} \sim 0.1 \text{ eV}$

Next Nearest neighbors
In momentum space
In momentum space
In momentum space

Dirac Cone
In momentum space

Dirac Cone

\[ E_\pm (p) = \pm v_F \sqrt{p_x^2 + p_y^2} = \pm v_F p \]

\[ E_\pm (p,m) = \pm \sqrt{m^2 v_F^4 + v_F^2 p^2} \quad \text{with} \quad m = 0 \]

\[ v_F = \frac{3ta}{2} \approx c / 300 \]
In momentum space

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\[ v_F = \frac{3ta}{2} \approx \frac{c}{300} \]
Mathematically

\[ H = v_F \begin{bmatrix} 0 & p_x - i p_y \\ p_x + i p_y & 0 \end{bmatrix} \]

\[ H \Psi_\pm(p) = \pm v_F p \Psi_\pm(p) \]

\[ \sigma \cdot u_p \Psi_\pm(p) = \pm \Psi_\pm(p) \]
Mathematically

\[
H = v_F \begin{bmatrix}
0 & p_x - i p_y \\
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H \Psi_{\pm}(p) = \pm v_F p \Psi_{\pm}(p)
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\sigma \cdot u_p \Psi_{\pm}(p) = \pm \Psi_{\pm}(p)
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Chirality (helicity)

+ = right handed; - = left handed
Mathematically

\[ H = v_F \begin{bmatrix} 0 & p_x - i p_y \\ p_x + i p_y & 0 \end{bmatrix} \]

\[ H \Psi_{\pm}(p) = \pm v_F p \Psi_{\pm}(p) \]

\[ \sigma \cdot u_p \Psi_{\pm}(p) = \pm \Psi_{\pm}(p) \]

Chirality (helicity)

\(+ = \) right handed; \(- = \) left handed
Mathematically

\[ H = v_F \begin{bmatrix} 0 & p_x - i p_y \\ p_x + i p_y & 0 \end{bmatrix} \quad H \Psi_\pm(p) = \pm v_F p \Psi_\pm(p) \]

\[ \sigma \cdot u_p \Psi_\pm(p) = \pm \Psi_\pm(p) \]

Chirality (helicity)

+ = right handed; - = left handed
What is the proof that Dirac fermions exist in graphene?
What is the proof that Dirac fermions exist in graphene?
Two-dimensional gas of massless Dirac fermions in graphene


Experimental observation of the quantum Hall effect and Berry’s phase in graphene

Yuanbo Zhang, Yan-Wen Tan, Horst L. Stormer & Philip Kim
Electric Field Effect in Atomically Thin Carbon Films

K.S. Novoselov¹, A.K. Geim¹, S.V. Morozov², D. Jiang¹, Y. Zhang¹, S.V. Dubonos², I.V. Grigorieva¹, A.A. Firsov²

¹Department of Physics, University of Manchester, M13 9PL, Manchester, UK
²Institute for Microelectronics Technology, 142432 Chernogolovka, Russia
Web of Science® – now with Conference Proceedings

Citation Report  Topic=(graphene)

This report reflects citations to source items indexed within Web of Science. Perform a Cited Reference Search to include citations to items not indexed within Web of Science.

Results found: 4,962
Sum of the Times
  Cited [?] : 83,130
  View Citing Articles
  View without self-citations
Average Citations
  per Item [?] : 16.75
  h-index [?] : 114
Graphene: Most Popular Material
## Graphene: Most Popular Material

<table>
<thead>
<tr>
<th>rank</th>
<th>search word</th>
<th>frequency</th>
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<tr>
<td>1</td>
<td>graphene</td>
<td>~3.0</td>
</tr>
<tr>
<td>2</td>
<td>cancer</td>
<td>~2.0</td>
</tr>
<tr>
<td>3</td>
<td>HIV</td>
<td>1.3</td>
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<tr>
<td>4</td>
<td>apoptosis</td>
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searches on all Nature websites during 2009
courtesy of Dr Peter Rogers (editor of Nature)
Graphene: Most Popular Material

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*searches on all Nature websites during 2009
courtesy of Dr Peter Rogers (editor of Nature)*
Electrons behave as massless relativistic particles.

Relativity at very low “speed of light”

Quantum Physics plus Relativity on a table-top!
Atomic Physics

\[ V(r) = -Z \frac{e^2}{\varepsilon_0 r} \quad \text{Coulomb law} \]
Atomic Physics

\[ V(r) = -Z \frac{e^2}{\varepsilon_0 r} \]  Coulomb law
Atomic Physics

\[ V(r) = -Z \frac{e^2}{\varepsilon_0 r} \]  Coulomb law

Fine structure constant

\[ \alpha = \frac{e^2}{\varepsilon_0 hc} = 0.007297352536(5) \approx \frac{1}{137} \]
Atomic Physics
Atomic Physics

\[ Z < \frac{1}{\alpha} \approx 137 \]
Atomic Physics

\[ Z < \frac{1}{\alpha} \approx 137 \]
Atomic Physics

\[ Z < \frac{1}{\alpha} \approx 137 \]

\[ Z > \frac{1}{\alpha} \approx 137 \]

Overcritical Atom

Positron emission
Periodic table of the elements

* Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC).
** Numbering system widely used, especially in the U.S., from the mid-20th century.
*** Discoveries of elements 112–116 are claimed but not confirmed. Element names and symbols in parentheses are temporarily assigned by IUPAC.
heavy ion collisions  neutron stars
But in graphene:
But in graphene:

\[ \alpha_G = \frac{e^2}{\varepsilon_0 h \nu} \approx 2 \]
But in graphene:

\[ \alpha_G = \frac{e^2}{\varepsilon_0 h\nu} \approx 2 \]

\[ Z > \frac{1}{\alpha_G} \approx 0.5 \]

Atoms become overcritical easily

Coulomb Impurity Problem in Graphene
PRL 99, 166802 (2007)
Vitor M. Pereira, Johan Nilsson, and A. H. Castro Neto
But in graphene:

\[ \alpha_G = \frac{e^2}{\varepsilon_0 h \nu} \approx 2 \]

Atoms become overcritical easily

\[ Z > \frac{1}{\alpha_G} \approx 0.5 \]

Coulomb Impurity Problem in Graphene
PRL 99, 166802 (2007)
Vitor M. Pereira, Johan Nilsson, and A. H. Castro Neto
Use a scanning tunneling microscope, for a "high-energy experiment"
Resonances indicate emission of anti-particles.
Graphene is one atom thick and hence soft!
Graphene is one atom thick and hence soft!

Graphene is one atom thick and hence soft!

Graphene has a tendency to be rough and have locally a finite curvature: folding, rippling, wrinkling...

Soft and hard condensed matter of graphene
Soft and hard condensed matter of graphene

\[ H_0 = iv_F \sigma \cdot \nabla \]
Soft and hard condensed matter of graphene

\[ H_0 = i v_F \sigma \cdot \nabla \]
Soft and hard condensed matter of graphene

\[ H_0 = i v_F \sigma \cdot \nabla \]

\[ H_M = \sigma \cdot (i v_F \nabla + A(r)) + \Phi(r) \]

\[ A(r) \propto \frac{n(\theta)}{R^2(r)} \quad \langle n(\theta) \rangle = 0 \]

\[ \Phi(r) \propto \frac{1}{R^2(r)} \]
Soft and hard condensed matter of graphene

\[ H_0 = i v_F \sigma \cdot \nabla \]

\[ H_M = \sigma \cdot (i v_F \nabla + A(r)) + \Phi(r) \]

\[ A(r) \propto \frac{n(\theta)}{R^2(r)} \quad \langle n(\theta) \rangle = 0 \]

\[ \Phi(r) \propto \frac{1}{R^2(r)} \quad B = \nabla \times A \]
Soft and hard condensed matter of graphene

\[ H_0 = i v_F \sigma \cdot \nabla \]

\[ H_M = \sigma \cdot (i v_F \nabla + A(r)) + \Phi(r) \]

\[ A(r) \propto \frac{n(\theta)}{R^2(r)} \]

\[ \langle n(\theta) \rangle = 0 \]

\[ \Phi(r) \propto \frac{1}{R^2(r)} \]

\[ B = \nabla \times A \]

Graphene is a metallic membrane

What about applications?
Moore’s Law Ending (Red Line): Delayed products, Delayed 45nm / 32 nm, Reduced Capex

EVERY 18 MONTHS
2300 \times 2^{0.5667 \times (Year - 1971)}

ITANIUM 2
WITH 9-MB CACHE

PENTIUM 4

FUTURE PATH IN COLOR

FUTURE TO 2018
2009
2015
2018

TRANISTORS/CHIP DOUBLING EVERY 2 YEARS
(WORKED OUT WELL, BUT NOT MUCH LONGER.)
N = 2300 \times 2^{0.5 \times (Year - 1971)}

Based on logistic regression, asymptote at 6.25 billion.

By Clayton Hallmark
Dedicated to Professor Frederick E. Terman
Tukwila (Intel)
February 2008
2 billion transistors
speed: 2 GHz
65 nm transistors
First Ge transistor

Modern Si MOSFET
Graphene Quantum Dots
Graphene Quantum Dots
Miniaturization down to 1 nm: a few benzene rings
Graphene Bilayer
Graphene Bilayer
Graphene Bilayer

Dirac Cone

Electric Field

Tunneling

GAP
Graphene Bilayer

Semiconductor tunable by electric field effect

![Graphene Bilayer Diagram](image)
Graphene Bilayer

Semiconductor tunable by electric field effect

Electronic properties of bilayer and multilayer graphene

PHYSICAL REVIEW B 78, 045405 (2008)

Johan Nilsson,\textsuperscript{1,2} A. H. Castro Neto,\textsuperscript{1} F. Guinea,\textsuperscript{3} and N. M. R. Peres\textsuperscript{4}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graphene_bilayer.png}
\caption{Graphene Bilayer Structure}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{electronic_properties.png}
\caption{Electronic Properties of Graphene}
\end{figure}
Hype or Hope ?
Detection of individual gas molecules adsorbed on graphene
Detection of individual gas molecules adsorbed on graphene


Hype or Hope?

Energy Band-Gap Engineering of Graphene Nanoribbons
Melinda Y. Han, Barbaros Özyilmaz, Yuanbo Zhang, and Philip Kim

PRL 98, 206805 (2007)
Fine Structure Constant Defines Visual Transparency of Graphene

R. R. Nair, P. Blake, A. N. Grigorenko, K. S. Novoselov, T. J. Booth, T. Stauber, N. M. R. Peres, A. K. Geim

Science 320: 1308.
Fine Structure Constant Defines Visual Transparency of Graphene

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*Science* 320: 1308.

Transparent, Conductive Graphene Electrodes for Dye-Sensitized Solar Cells

Xuan Wang, Linjie Zhi, and Klaus Müllen

Graphene-Based Single-Bacterium Resolution Biodevice and DNA Transistor: Interfacing Graphene Derivatives with Nanoscale and Microscale Biocomponents

Nihar Mohanty and Vikas Berry

Nano Letters 8: 4469–76
Graphene-Based Single-Bacterium Resolution Biodevice and DNA Transistor: Interfacing Graphene Derivatives with Nanoscale and Microscale Biocomponents
Nihar Mohanty and Vikas Berry
Nano Letters 8: 4469–76

Graphene-Based Ultracapacitors
Meryl D. Stoller, Sungjin Park, Yanwu Zhu, Jinho An and Rodney S. Ruof
Graphene and Mobile Ions: The Key to All-Plastic, Solution-Processed Light-Emitting Devices

Piotr Matyba, Hisato Yamaguchi, Goki Eda, Manish Chhowalla, Ludvig Edman and Nathaniel D. Robinson

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Rapid Sequencing of Individual DNA Molecules in Graphene Nanogaps
Henk W. Ch. Postma
100-GHz Transistors from Wafer-Scale Epitaxial Graphene


5 FEBRUARY 2010 VOL 327 SCIENCE

A

D

Current Gain $|h_{21}|$

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GHz</td>
</tr>
</tbody>
</table>

$1/f$

Gate length

- 240 nm
- 550 nm

Source drain

Gate

Dielectric

Graphene

SIC

Frequency [GHz]
Atomic-Layer Graphene as a Saturable Absorber for Ultrafast Pulsed Lasers

By Qiaoliang Bao, Han Zhang, Yu Wang, Zhenhua Ni, Yongli Yan, Ze Xiang Shen, Kian Ping Loh,* and Ding Yuan Tang*
On the market...
Future Directions for Graphene Research

Chemistry and Materials Science

Tailoring graphene’s electronic properties:

- **Paper-cutting:** Structural engineering
- **Decorating:** Band structure engineering
- **Origami:** Strain engineering
Future Directions for Graphene Research

Chemistry and Materials Science
Tailoring graphene’s electronic properties:

*Paper-cutting:* Structural engineering
*Decorating:* Band structure engineering
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Chemistry and Materials Science
Tailoring graphene’s electronic properties:

*Paper-cutting*: Structural engineering

*Decorating*: Band structure engineering

*Origami*: Strain engineering
The rise of graphene... Much more to come ....