Grafeno e nanomateriais relacionados

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Departamento de Física – UFES

Sumário

- Um pouco de história sobre a “descoberta” do grafeno.
- Estrutura e propriedades físicas do grafeno.
- Produção de grafeno e outros materiais bidimensionais.
- Aplicações (reais, potenciais e sonhos…)

O Prêmio Nobel de Física de 2010

Os laureados:

Andre Geim e Konstantin Novoselov

"...for groundbreaking experiments regarding the two-dimensional material graphene."

http://nobelprize.org/nobel_prizes/physics/laureates/2010/

O Prêmio Nobel de Física de 2010

Os laureados:

Andre Geim

Nascimento: 1958, Sochi, Rússia.
Instituição: Universidade de Manchester.

Konstantin Novoselov

Nascimento: 1974, Nizhny Tagil, Rússia.
Instituição: Universidade de Manchester.

http://nobelprize.org/nobel_prizes/physics/laureates/2010/

O Prêmio Nobel de Física de 2010

Sobre os trabalhos de Andre Geim: levitação magnética.

http://static.nobelprize.org/nobel_prizes/physics/laureates/2010/geim-lecture-slides.pdf

O Prêmio Nobel de Física de 2010

Sobre os trabalhos de Andre Geim: levitação magnética.

Eur. J. Phys. 18 (1997) 307–313. Printed in the UK   PII: S0143-0807(97)84689-2

Of flying frogs and levitrons

M V Berry† and A K Geim‡

† H H Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, UK
‡ High Field Magnet Laboratory, Department of Physics, University of Nijmegen, Toernooiveld, 6525 ED Nijmegen, The Netherlands

Received 4 June 1997

Figure 4(*b*). Frog levitated in the stable region.

The 2000 Ig Nobel Prize Winners

(Click here for details about the ceremony)

PSYCHOLOGY
David Dunning of Cornell University and Justin Kruger of the University of Illinois, for their modest report, "Unskilled and Unaware of It: How Difficulties in Recognizing One's Own Incompetence Lead to Inflated Self-Assessments." [Published in the Journal of Personality and Social Psychology, vol. 77, no. 6, December 1999, pp. 1121-34.]

LITERATURE
Jasmuheen (formerly known as Ellen Greve) of Australia, first lady of Breatharianism, for her book "Living on Light," which explains that although some people do eat food, they don't ever really need to.

BIOLOGY
Richard Wassersug of Dalhousie University, for his first-hand report, "On the Comparative Palatability of Some Dry-Season Tadpoles from Costa Rica." [Published in The American Midland Naturalist, vol. 86, no. 1, July 1971, pp. 101-9.]

PHYSICS
Andre Geim of the University of Nijmegen (the Netherlands) and Sir Michael Berry of Bristol University (UK), for using magnets to levitate a frog. [REFERENCE: "Of Flying Frogs and Levitrons" by M.V. Berry and A.K. Geim, European Journal of Physics, v. 18, 1997, p. 307-13.]
NOTE: Ten years later, in 2010, Andre Geim won a Nobel Prize in physics (for research on another subject).

CHEMISTRY
Donatella Marazziti, Alessandra Rossi, and Giovanni B. Cassano of the University of Pisa, and Hagop S. Akiskal of the University of California (San Diego), for their discovery that, biochemically, romantic love may be indistinguishable from having severe obsessive-compulsive disorder. [REFERENCE: "Alteration of the platelet serotonin transporter in romantic love," Marazziti D, Akiskal HS, Rossi A, Cassano GB, Psychological Medicine, 1999 May;29(3):741-5.]

ECONOMICS
The Reverend Sun Myung Moon, for bringing efficiency and steady growth to the mass-marriage industry, with, according to his reports, a 36-couple wedding in 1960, a 430-couple wedding in 1968, an 1800-couple wedding in 1975, a 6000-couple wedding in 1982, a 30,000-couple wedding in 1992, a 360,000-couple wedding in 1995, and a 36,000,000-couple wedding in 1997.

MEDICINE
Willibrord Weijmar Schultz, Pek van Andel, and Eduard Mooyaart of Groningen, The Netherlands, and Ida Sabelis of Amsterdam, for their illuminating report, "Magnetic Resonance Imaging of Male and Female Genitals During Coitus and Female Sexual Arousal." [Published in British Medical Journal, vol. 319, 1999, pp 1596-1600.]

COMPUTER SCIENCE
Chris Niswander of Tucson, Arizona, for inventing PawSense, software that detects when a cat is walking across your computer keyboard.

PEACE
The British Royal Navy, for ordering its sailors to stop using live cannon shells, and to instead just shout "Bang!"

PUBLIC HEALTH
Jonathan Wyatt, Gordon McNaughton, and William Tullet of Glasgow, for their alarming report, "The Collapse of Toilets in Glasgow." [Published in the Scottish Medical Journal, vol. 38, 1993, p. 185.]

http://improbable.com/ig/winners/#ig2000

O trabalho original de Geim & Novoselov

Electric Field Effect in Atomically Thin Carbon Films
K. S. Novoselov, *et al.*
Science **306**, 666 (2004);
DOI: 10.1126/science.1102896

Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1]* S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

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 ~10,000 square centimeters per volt-second can be induced by applying gate voltage.

Novoselov et al., *Science* 2004;306:666-669

O trabalho original de Geim & Novoselov

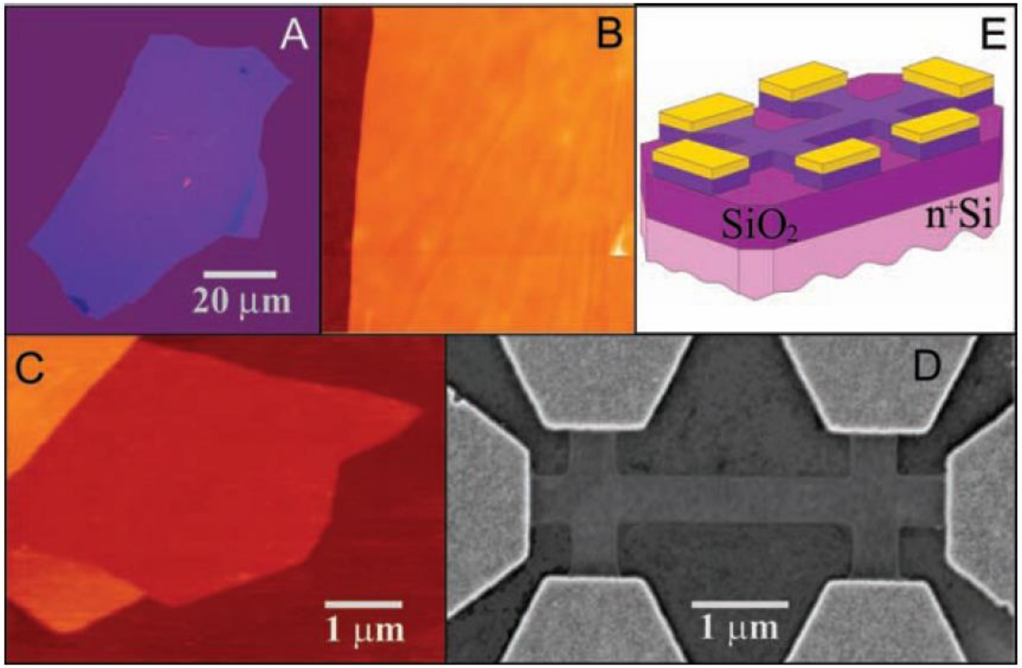
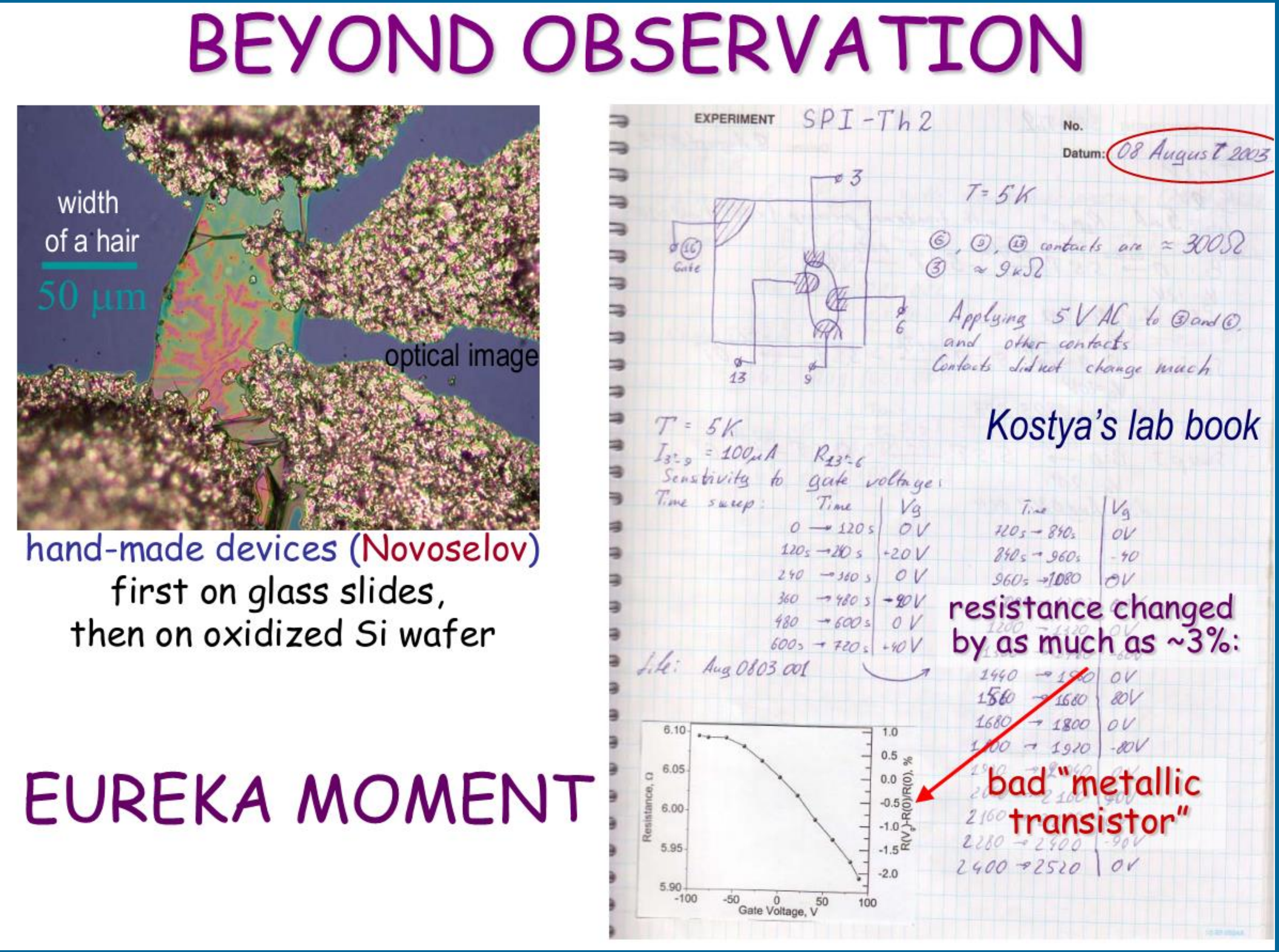


Fig. 1. Graphene films. (**A**) Photograph (in normal white light) of a relatively large multilayer graphene flake with thickness ~3 nm on top of an oxidized Si wafer. (**B**) Atomic force microscope (AFM) image of 2 μm by 2 μm area of this flake near its edge. Colors: dark brown, SiO_2 surface; orange, 3 nm height above the SiO_2 surface. (**C**) AFM image of single-layer graphene. Colors: dark brown, SiO_2 surface; brown-red (central area), 0.8 nm height; yellow-brown (bottom left), 1.2 nm; orange (top left), 2.5 nm. Notice the folded part of the film near the bottom, which exhibits a differential height of ~0.4 nm. For details of AFM imaging of single-layer graphene, see (*15*). (**D**) Scanning electron microscope image of one of our experimental devices prepared from FLG. (**E**) Schematic view of the device in (D).

Novoselov et al., *Science* 2004;306:666-669

O trabalho original de Geim & Novoselov



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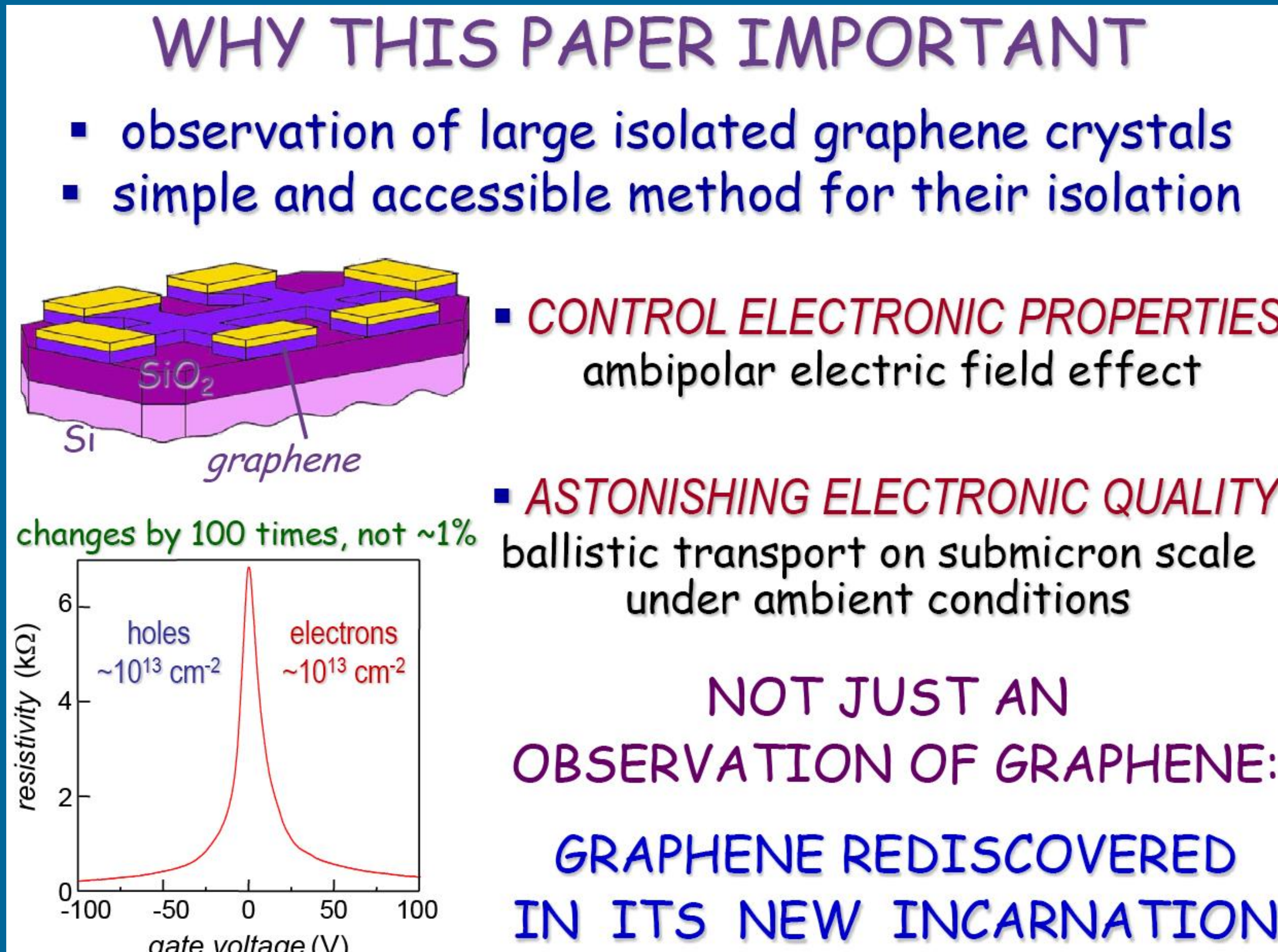
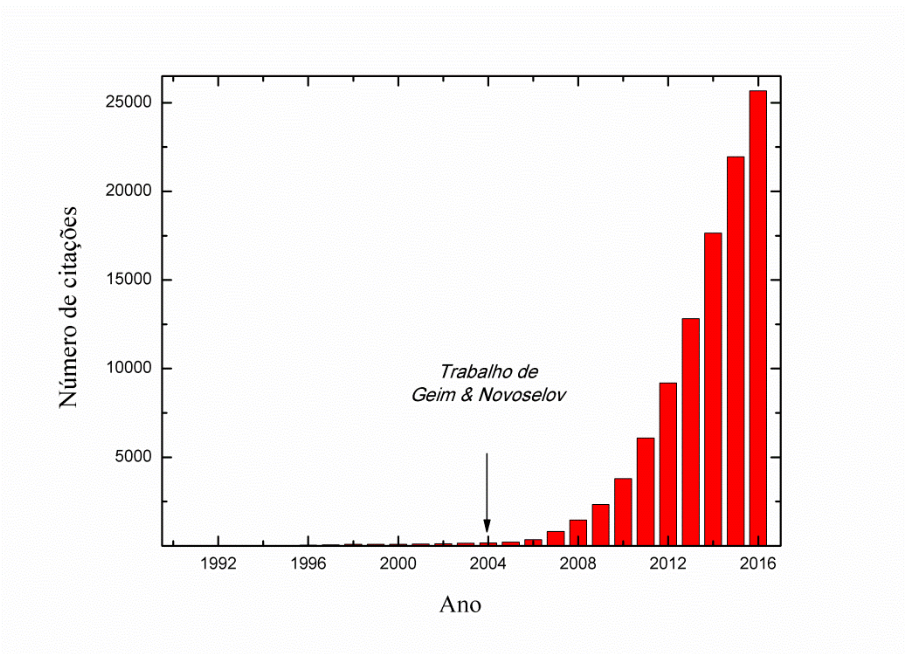
O trabalho original de Geim & Novoselov

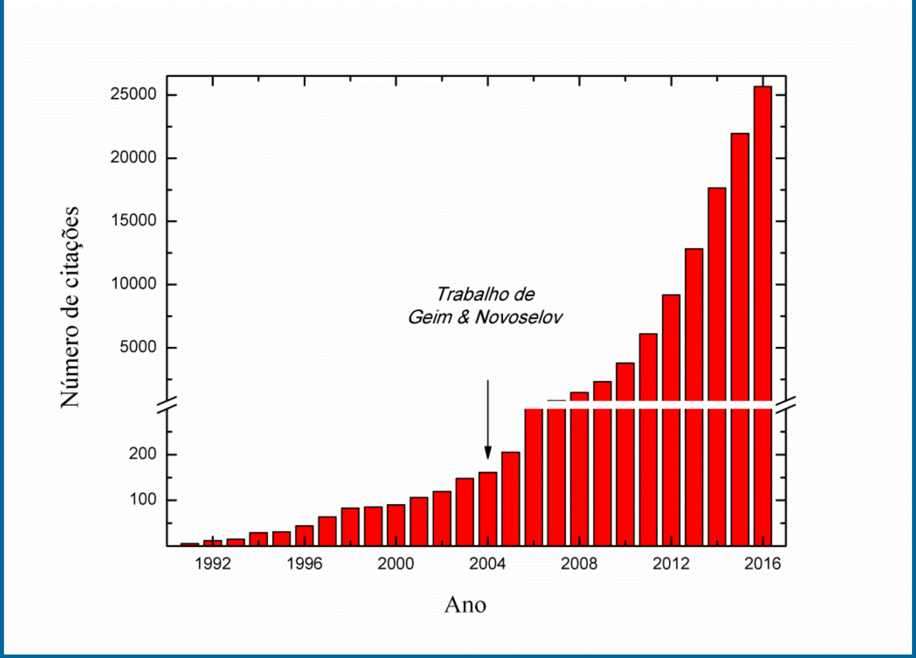


http://static.nobelprize.org/nobel_prizes/physics/laureates/2010/geim-lecture-slides.pdf

Citações científicas sobre o grafeno

Citações anuais em artigos científicos da palavra “graphene”:





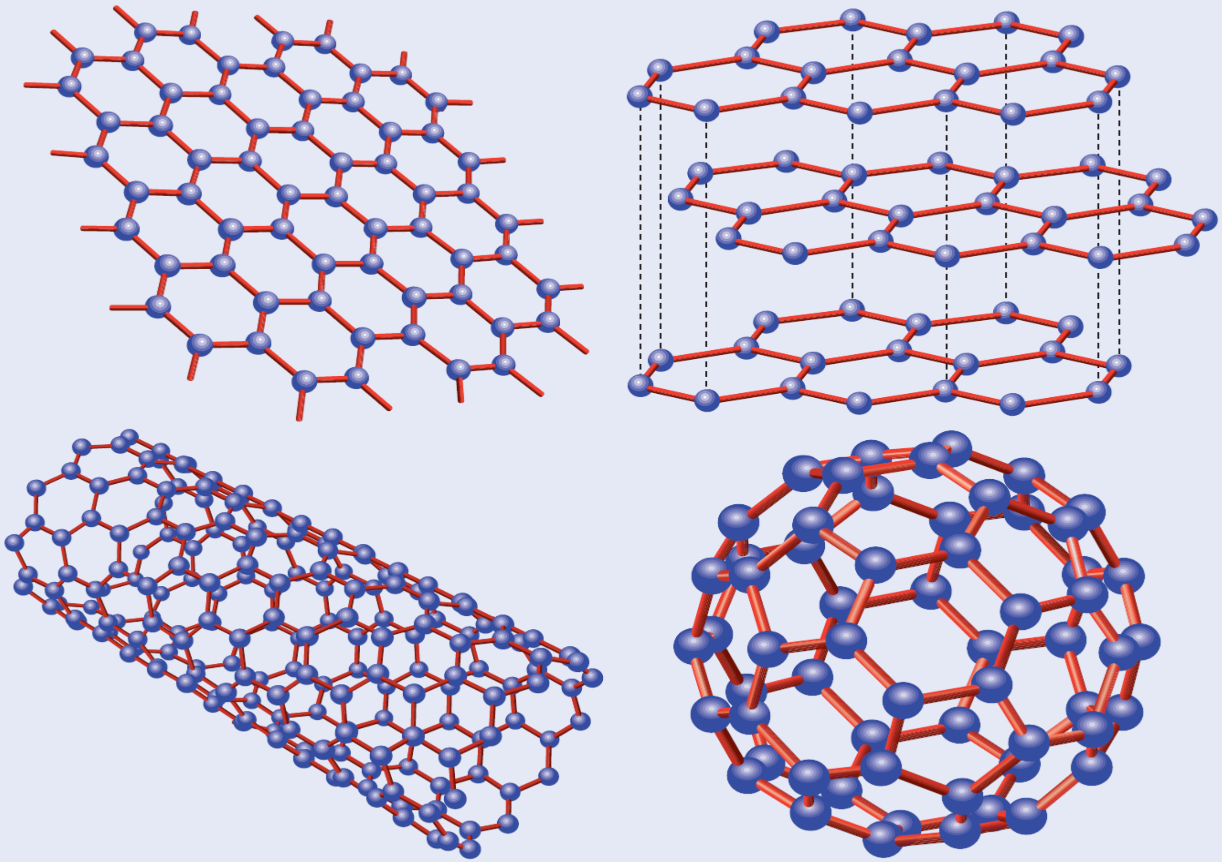
Fonte: ISI Web of Knowledge

Propriedades peculiares e superlativas do grafeno

- Propriedades mecânicas: material mais fino possível, extremamente forte, porém flexível, baixa densidade, alta área superficial específica.
- Propriedades térmicas: elevada condutividade térmica.
- Propriedades químicas: alta pureza, estável em condições ambientes, quimicamente inerte, sensível à presença de moléculas adsorvidas.
- Propriedades eletrônicas: boa condutividade elétrica, portadores de carga sem massa efetiva, elevada mobilidade intrínseca, transporte eletrônico balístico, sensibilidade à aplicação de campos elétricos, efeito Hall quântico em temperatura ambiente ...
- Propriedades óticas: condutor elétrico oticamente transparente.
- Propriedades magnéticas: ferromagnetismo (elétrons *p*) induzido por defeitos estruturais.

Grafeno e outras formas de carbono

2 Graphene: mother of them all



Graphene (top left) consists of a 2D hexagonal lattice of carbon atoms. Each atom is covalently bonded to three others; but since carbon has four valence electrons, one is left free – allowing graphene to conduct electricity. Other well-known forms of carbon all derive from graphene: graphite is a stack of graphene layers (top right); carbon nanotubes are rolled-up cylinders of graphene (bottom left); and a buckminsterfullerene (C_{60}) molecule consists of graphene balled into a sphere by introducing some pentagons as well as hexagons into the lattice (bottom right).

Castro Neto et al., *Physics World* 2006;11:33-37

Grafeno e outras formas de carbono

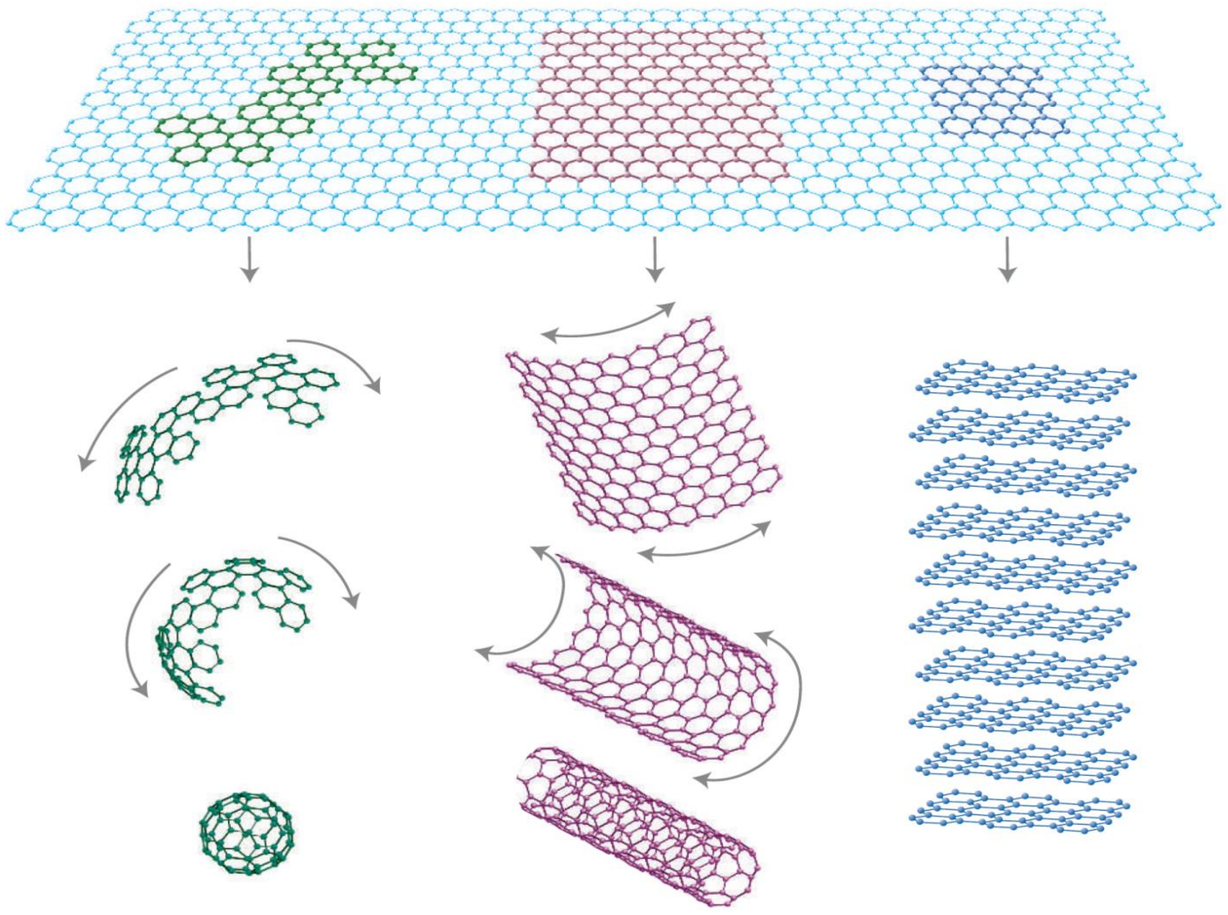
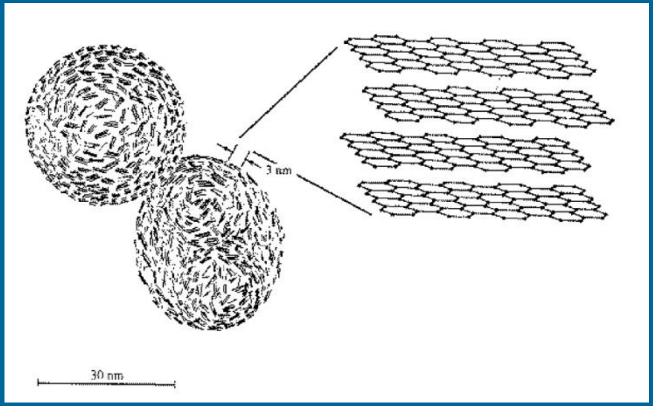


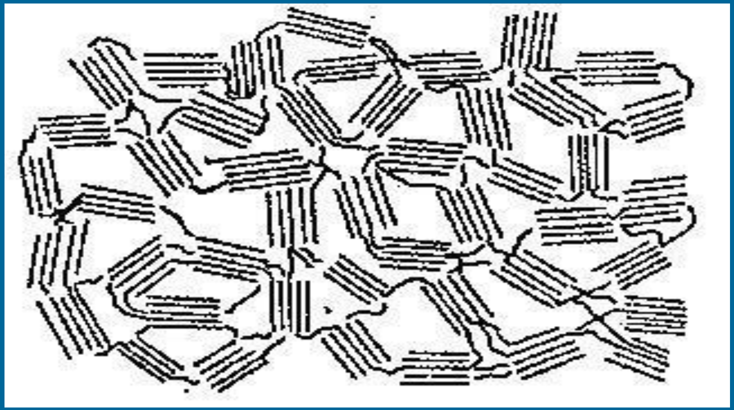
Figure 1 Mother of all graphitic forms. Graphene is a 2D building material for carbon materials of all other dimensionalities. It can be wrapped up into 0D buckyballs, rolled into 1D nanotubes or stacked into 3D graphite.

Geim & Novoselov, *Nature Materials* 2007;6:183-191

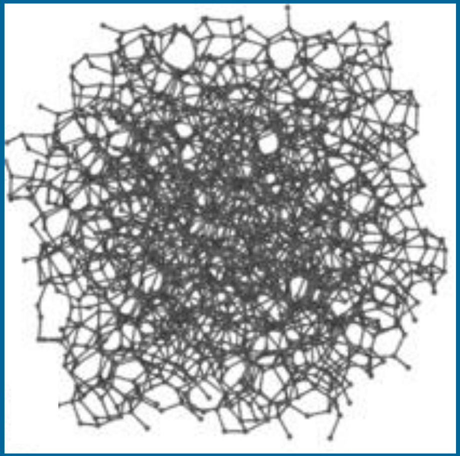
Grafeno e outras formas de carbono



Carbon blacks



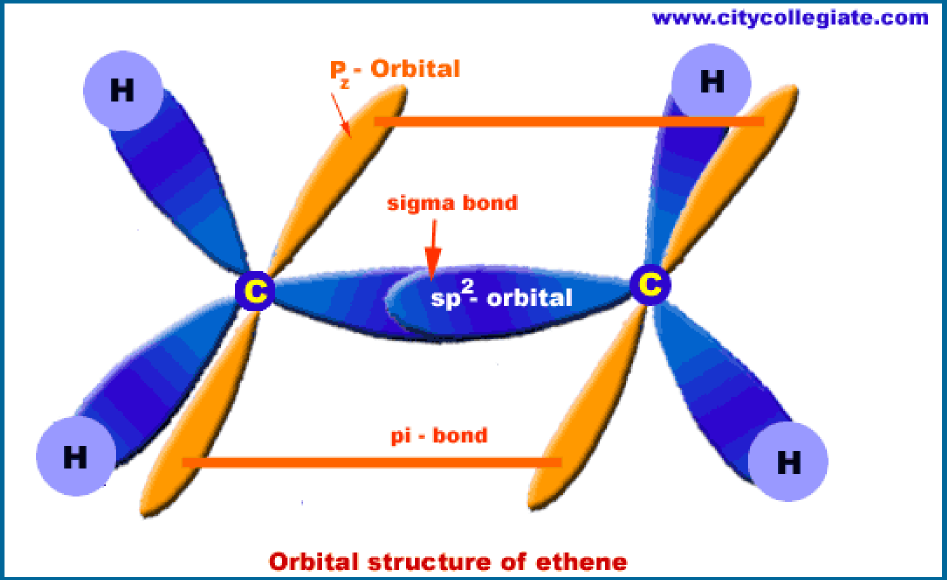
Materiais desordenados – estrutura turbostrática



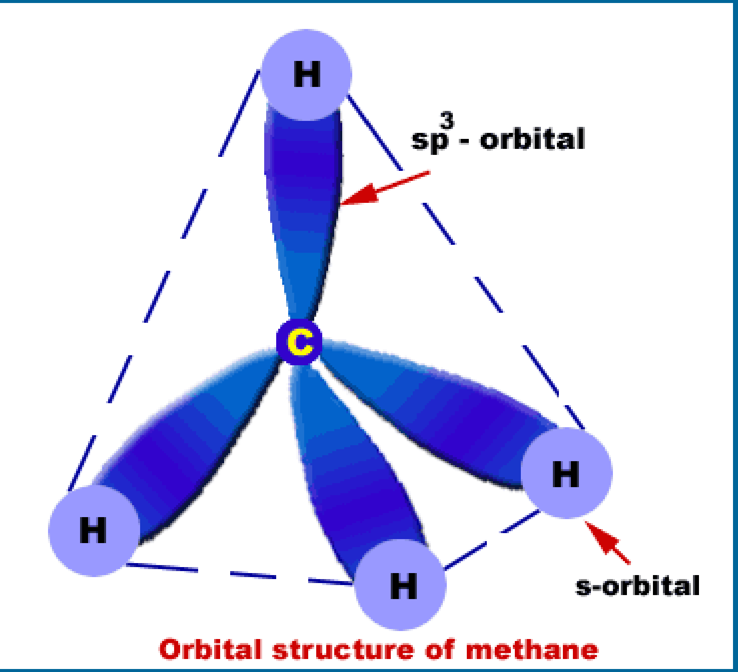
Carbono amorfo

Estrutura do grafeno

Hibridização sp^2:



Hibridização sp^3:;



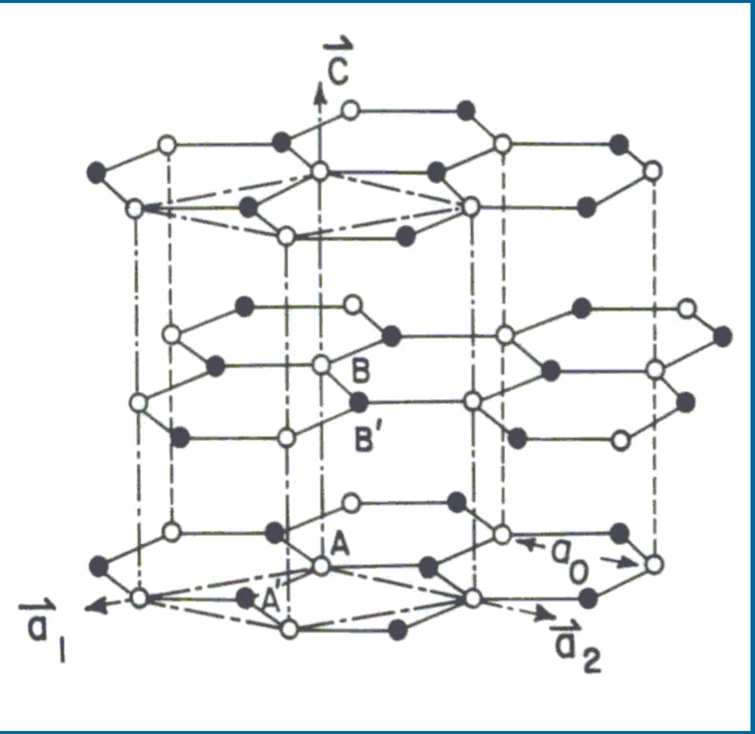
http://www.citycollegiate.com/hybridization1.htm

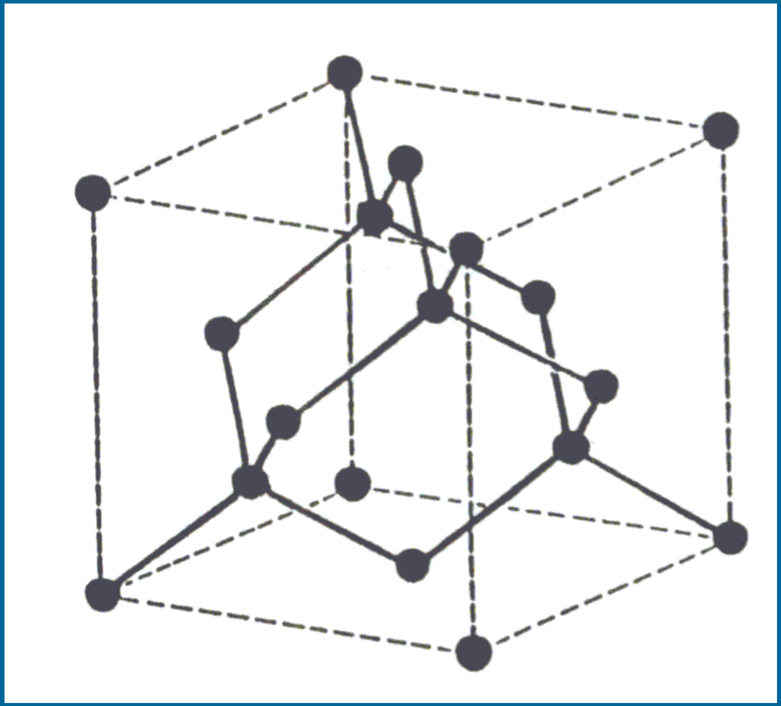
Grafite:

- ✓ Hibridização sp^2
- ✓ Estrutura hexagonal
- ✓ Anisotropia (planos grafenos)

Diamante:

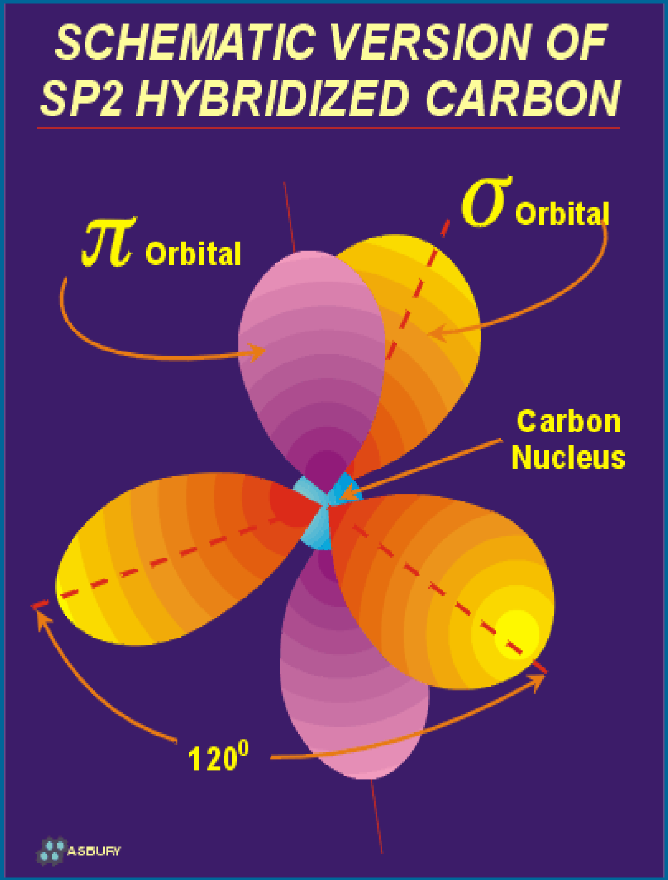
- ✓ Hibridização sp^3
- ✓ Estrutura cúbica (fcc)
- ✓ Isotrópico





Estrutura do grafeno

Hibridização sp^2:



Funções de onda dos orbitais híbridos:

$$\psi_1 = \frac{1}{\sqrt{3}}\varphi_{2s} + \sqrt{\frac{2}{3}}\varphi_{2p_x}$$

$$\psi_2 = \frac{1}{\sqrt{3}}\varphi_{2s} - \frac{1}{\sqrt{6}}\varphi_{2p_x} + \frac{1}{\sqrt{2}}\varphi_{2p_y}$$

$$\psi_3 = \frac{1}{\sqrt{3}}\varphi_{2s} - \frac{1}{\sqrt{6}}\varphi_{2p_x} - \frac{1}{\sqrt{2}}\varphi_{2p_y}$$

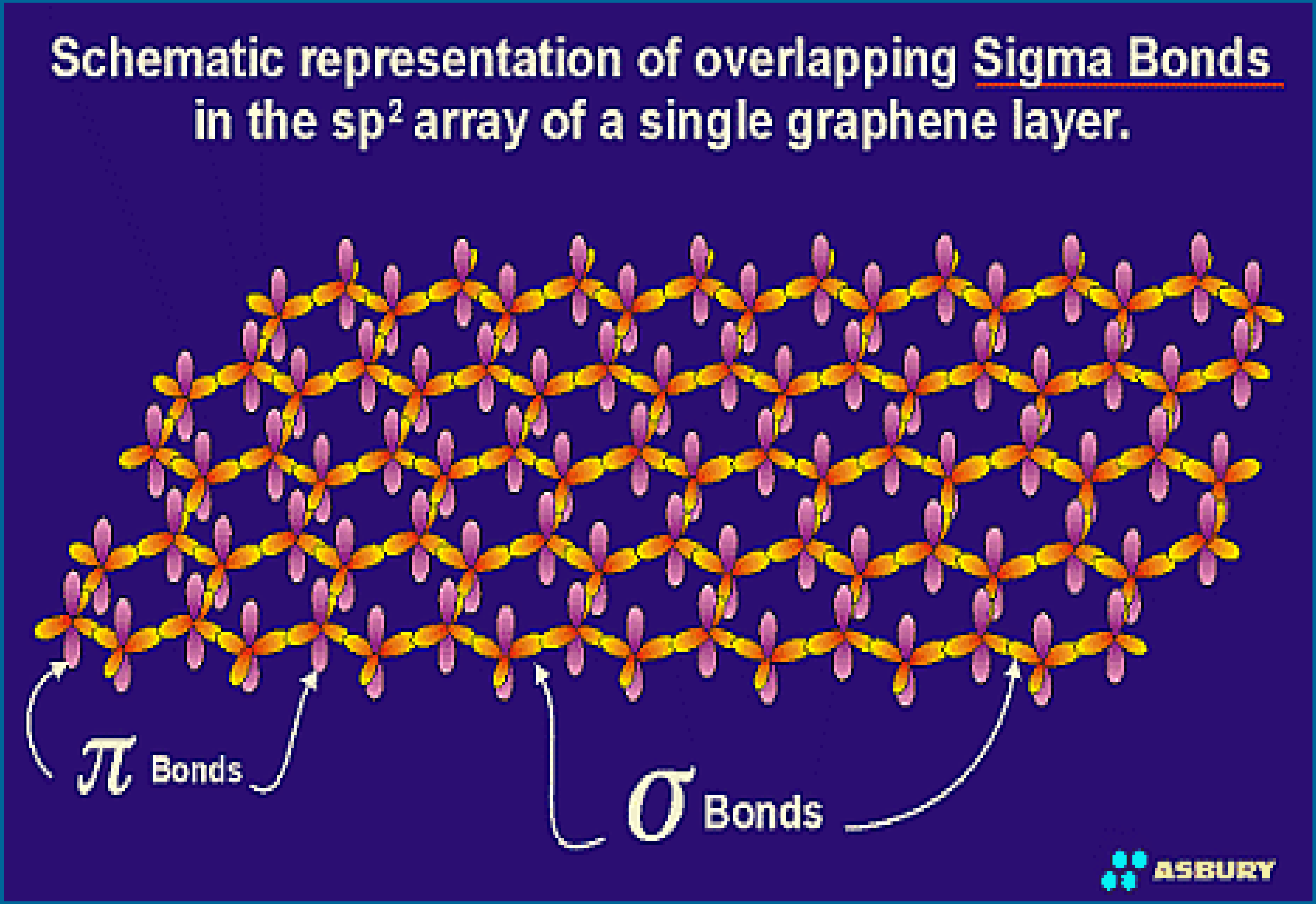
$$\psi_4 = \varphi_{2p_z}$$

Orbitais σ (ψ_1, ψ_2, ψ_3)

Orbital π (ψ_4)

http://www.asbury.com/Table/Introduction-to-Graphite/

Estrutura do grafeno



http://www.asbury.com/Table/Introduction-to-Graphite/

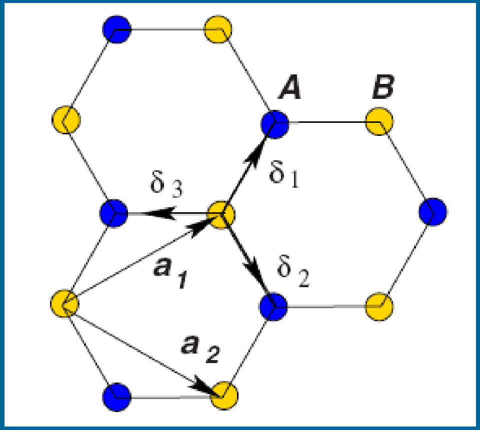
Estrutura do grafeno – bandas de energia

Funções de Bloch construídas a partir dos orbitais atômicos:

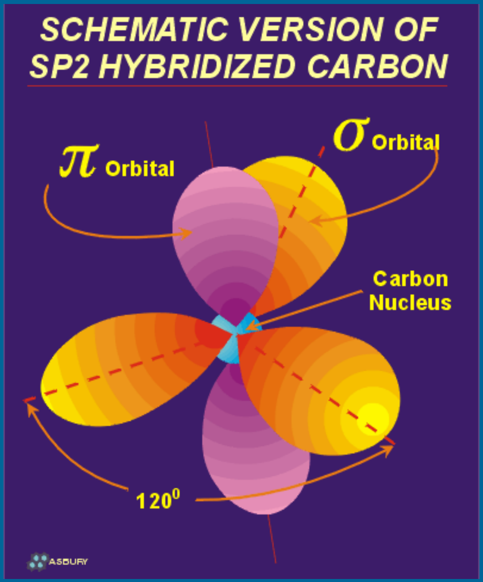
Orbital π $\psi_4 = \varphi_{2p_z} \equiv \varphi$

$$\psi_{\vec{k}}^{A}(\vec{r}) = \frac{1}{\sqrt{N}} \sum_{A} e^{i\vec{k}\cdot\vec{r}_A} \varphi(\vec{r} - \vec{r}_A)$$

$$\psi_{\vec{k}}^{B}(\vec{r}) = \frac{1}{\sqrt{N}} \sum_{B} e^{i\vec{k}\cdot\vec{r}_B} \varphi(\vec{r} - \vec{r}_B)$$



Castro Neto et al., *Rev. Mod. Phys.* 2009;81:109-162



http://www.asbury.com/Table/Introduction-to-Graphite/

Estrutura do grafeno – bandas de energia

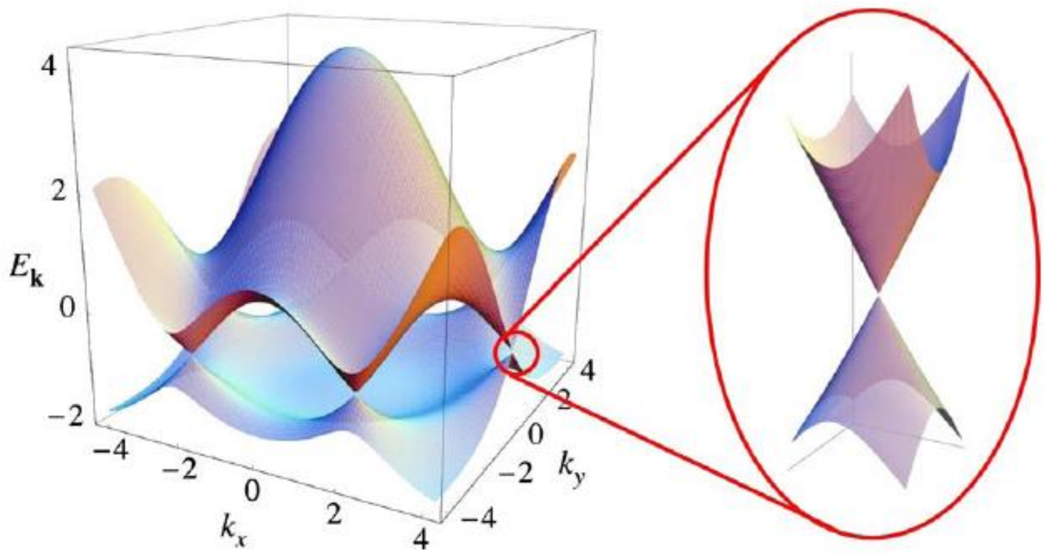
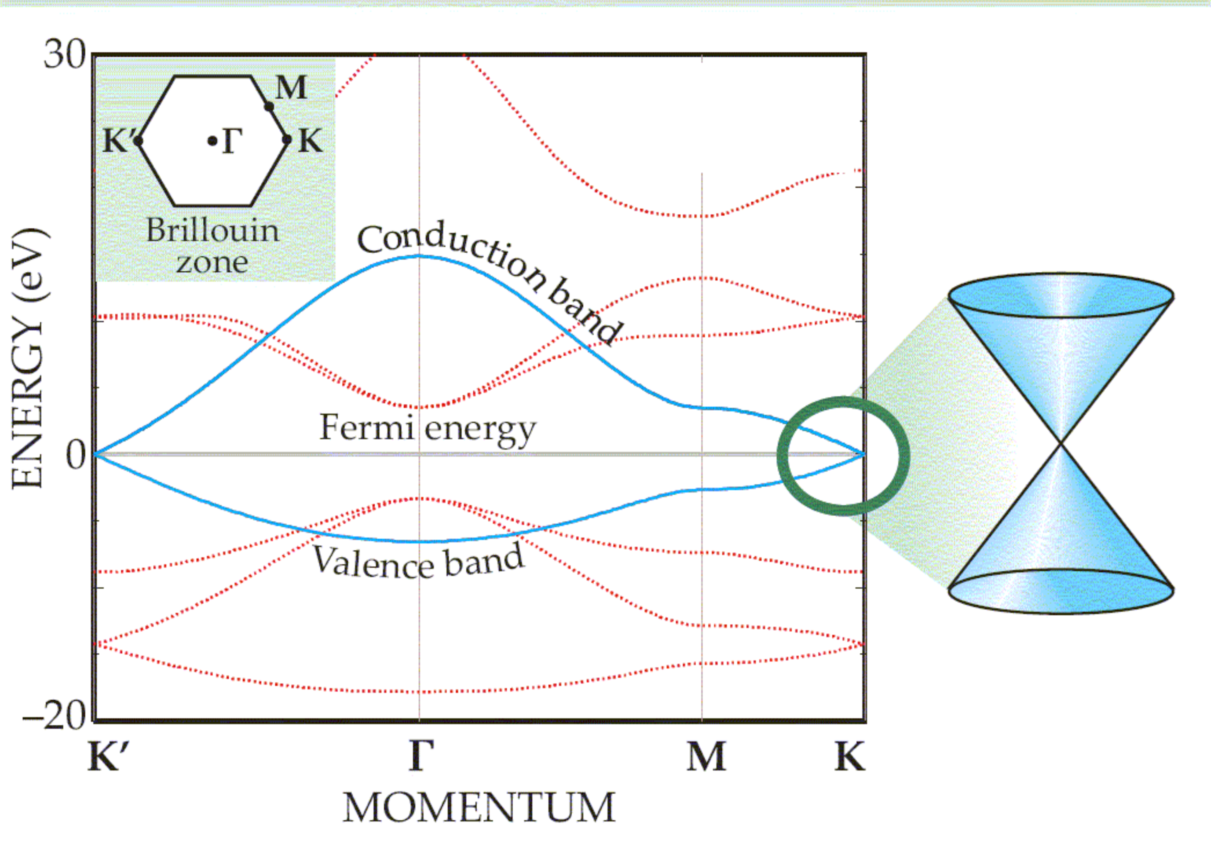


FIG. 3. (Color online) Electronic dispersion in the honeycomb lattice. Left: energy spectrum (in units of t) for finite values of t and t', with $t=2.7$ eV and $t'=-0.2t$. Right: zoom in of the energy bands close to one of the Dirac points.

Castro Neto et al., *Rev. Mod. Phys.* 2009;81:109-162

Estrutura do grafeno – bandas de energia

Soluções para as bandas de energia:



Cones de Dirac:

$$\varepsilon(\vec{q}) = \pm \frac{3}{2}\gamma_0 a \left|\vec{q}\right|$$

Geim & MacDonald, *Phys. Today* 2007;60:35-40

Estrutura do grafeno – bandas de energia

Cones de Dirac – relação de dispersão linear:

$$\varepsilon(\vec{q}) = \pm \frac{3}{2}\gamma_0 a |\vec{q}|$$

$$\vec{v} = \frac{1}{\hbar}\vec{\nabla}_{\vec{q}}\varepsilon(\vec{q})$$

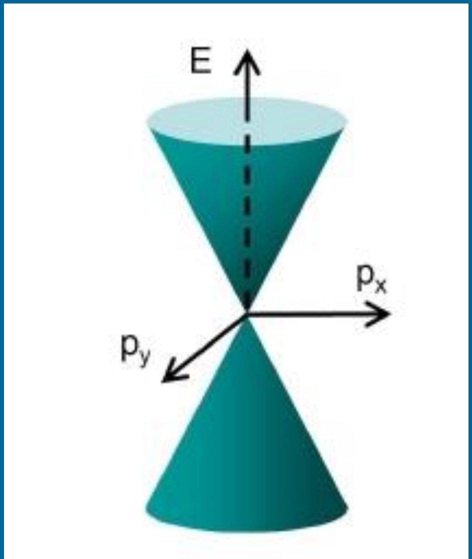
Velocidade de Fermi:

$$v_F = 3\gamma_0 a / 2\hbar \cong 1\times 10^6 m/s$$

$$\varepsilon = \hbar v_F q = v_F p$$

$$\frac{v_F}{c} \sim 0{,}003$$

Fótons: $E = \hbar c k = cp$



http://math.ucr.edu/home/baez/week277.html

Elétrons (e buracos) no grafeno (*quase-partículas*):

- **Férmions sem massa**.
- Comportamento quântico-relativístico – *Equação de Dirac*.
- Velocidade efetiva não relativística.

Estrutura do grafeno – bandas de energia

Comportamento quântico-relativístico dos elétrons no grafeno:

Vol 438|10 November 2005|doi:10.1038/nature04233 nature

LETTERS

Two-dimensional gas of massless Dirac fermions in graphene

K. S. Novoselov[1], A. K. Geim[1], S. V. Morozov[2], D. Jiang[1], M. I. Katsnelson[3], I. V. Grigorieva[1], S. V. Dubonos[2] & A. A. Firsov[2]

Quantum electrodynamics (resulting from the merger of quantum mechanics and relativity theory) has provided a clear understanding of phenomena ranging from particle physics to cosmology and from astrophysics to quantum chemistry[1–3]. The ideas underlying quantum electrodynamics also influence the theory of condensed matter[4,5], but quantum relativistic effects are usually minute in the known experimental systems that can be described accurately by the non-relativistic Schrödinger equation. Here we report an experimental study of a condensed-matter system (graphene, a single atomic layer of carbon[6,7]) in which electron transport is essentially governed by Dirac's (relativistic) equation. The charge carriers in graphene mimic relativistic particles with zero rest mass and have an effective 'speed of light' $c_* \approx 10^6\,\mathrm{m\,s^{-1}}$. Our study reveals a variety of unusual phenomena that are characteristic of two-dimensional Dirac fermions. In particular we have observed the following: first, graphene's conductivity never falls below a minimum value corresponding to the quantum unit of conductance, even when concentrations of charge carriers tend to zero; second, the integer quantum Hall effect in graphene is anomalous in that it occurs at half-integer filling factors; and third, the cyclotron mass m_c of massless carriers in graphene is described by $E = m_c c_*^2$. This two-dimensional system is not only interesting in itself but also allows access to the subtle and rich physics of quantum electrodynamics in a bench-top experiment.

Estrutura do grafeno – bandas de energia

Comportamento quântico-relativístico dos elétrons no grafeno:

PHYSICAL REVIEW
LETTERS

VOLUME 53 | 24 DECEMBER 1984 | NUMBER 26

Condensed-Matter Simulation of a Three-Dimensional Anomaly

Gordon W. Semenoff
The Institute for Advanced Study, Princeton, New Jersey 08540, and Department of Physics,[a]
University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
(Received 4 September 1984)

A condensed-matter analog of $(2+1)$-dimensional electrodynamics is constructed, and the consequences of a recently discovered anomaly in such systems are discussed.

The model considered here has been used extensively to study the electromagnetic properties of graphite.[13] Graphite is a semimetal which to a first approximation is composed of independent layers of carbon atoms. Each layer forms a honeycomb lattice with one valence electron per atomic site. In the planar material, the existence of two degeneracy points per Brillouin zone is a general consequence of the lattice symmetries.[14] Here, we shall present a simple dynamical model where this degeneracy is

explicit. In three-dimensional graphite, interplanar interactions break the symmetry,[15] and this model may not be strictly applicable there. However, there may be various types of intercalated or exfoliated graphite where the interplanar coupling is negligible. Furthermore, it may be possible to fabricate a graphite monolayer where the effects which we describe would be observable.

Propriedades eletrônicas do grafeno

Comportamento ambipolar:

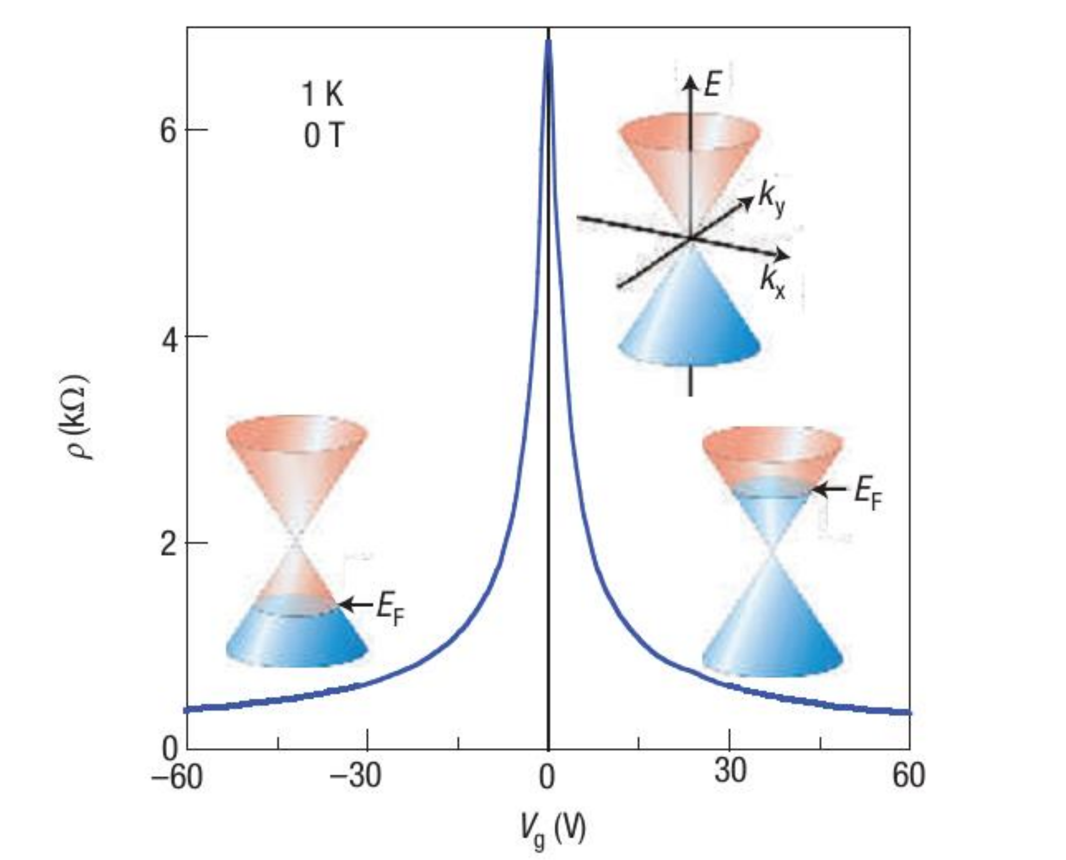


Figure 3 Ambipolar electric field effect in single-layer graphene. The insets show its conical low-energy spectrum $E(k)$, indicating changes in the position of the Fermi energy E_F with changing gate voltage V_g. Positive (negative) V_g induce electrons (holes) in concentrations $n = \alpha V_g$ where the coefficient $\alpha \approx 7.2\times10^{10}$ cm^{-2} V^{-1} for field-effect devices with a 300 nm SiO_2 layer used as a dielectric[7–9]. The rapid decrease in resistivity ρ on adding charge carriers indicates their high mobility (in this case, $\mu \approx 5{,}000$ cm^2 V^{-1} s^{-1} and does not noticeably change with increasing temperature to 300 K).

Geim & Novoselov, *Nature Materials* 2007;6:183-191

Propriedades eletrônicas do grafeno

Comportamento quântico-relativístico dos elétrons no grafeno:

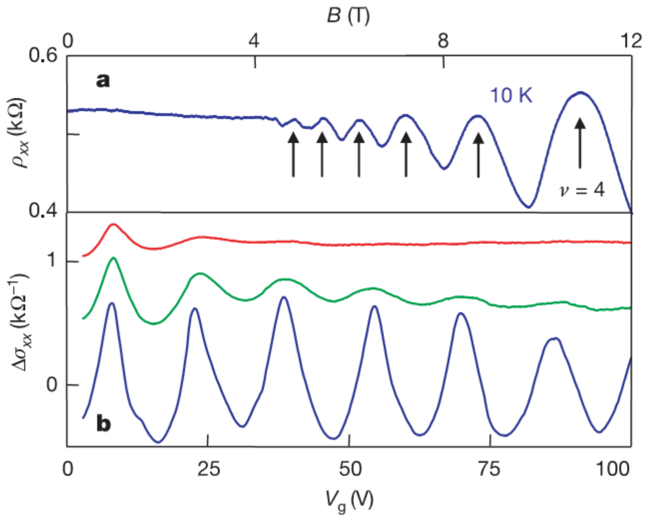


Figure 2 | Quantum oscillations in graphene. SdHO at constant gate voltage $V_g = -60$ V as a function of magnetic field B (**a**) and at constant $B = 12$ T as a function of V_g (**b**). Because μ does not change greatly with V_g, the measurements at constant B (at a constant $\omega_c\tau = \mu B$) were found more informative. In **b**, SdHOs in graphene are more sensitive to T at high carrier concentrations: blue, $T = 20$ K; green, $T = 80$ K; red, $T = 140$ K. The $\Delta\sigma_{xx}$ curves were obtained by subtracting a smooth (nearly linear) increase in σ with increasing V_g and are shifted for clarity. SdHO periodicity ΔV_g at constant B is determined by the density of states at each Landau level ($\alpha\Delta V_g = fB/\phi_0$), which for the observed periodicity of ~15.8 V at $B = 12$ T yields a quadruple degeneracy. Arrows in **a** indicate integer ν (for example, $\nu = 4$ corresponds to 10.9 T) as found from SdHO frequency $B_F \approx 43.5$ T. Note the absence of any significant contribution of universal conductance fluctuations (see also Fig. 1) and weak localization magnetoresistance, which are normally intrinsic for 2D materials with so high resistivity.

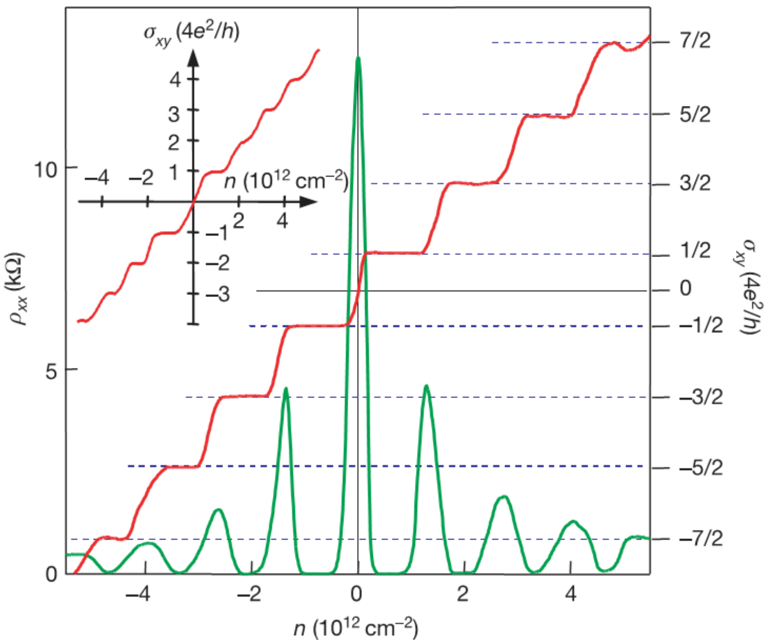
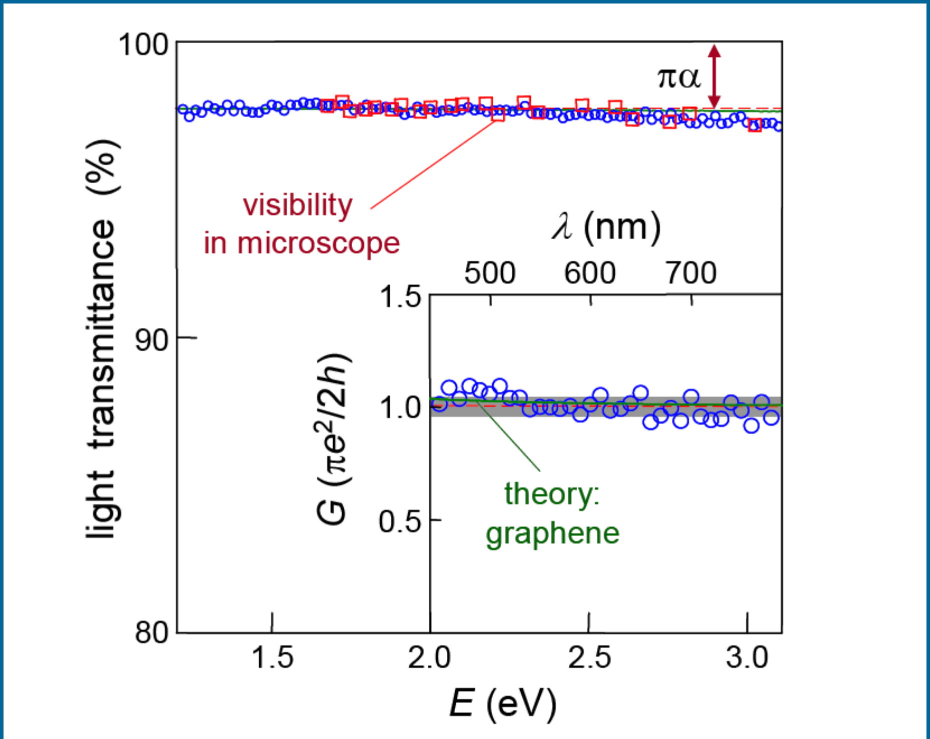


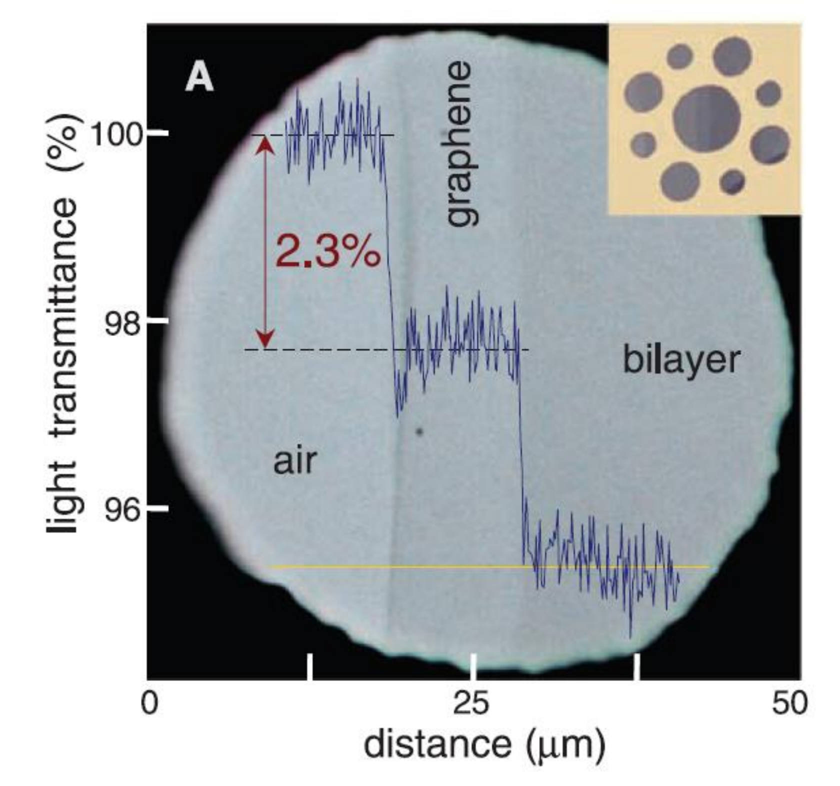
Figure 4 | QHE for massless Dirac fermions. Hall conductivity σ_{xy} and longitudinal resistivity ρ_{xx} of graphene as a function of their concentration at $B = 14$ T and $T = 4$ K. $\sigma_{xy} \equiv (4e^2/h)\nu$ is calculated from the measured dependences of $\rho_{xy}(V_g)$ and $\rho_{xx}(V_g)$ as $\sigma_{xy} = \rho_{xy}/(\rho_{xy}^2 + \rho_{xx}^2)$. The behaviour of $1/\rho_{xy}$ is similar but exhibits a discontinuity at $V_g \approx 0$, which is avoided by plotting σ_{xy}. Inset: σ_{xy} in 'two-layer graphene' where the quantization sequence is normal and occurs at integer ν. The latter shows that the half-integer QHE is exclusive to 'ideal' graphene.

Novoselov et al., *Nature* 2005;438:197-200

Propriedades óticas do grafeno

Obtenção da constante de estrutura fina:



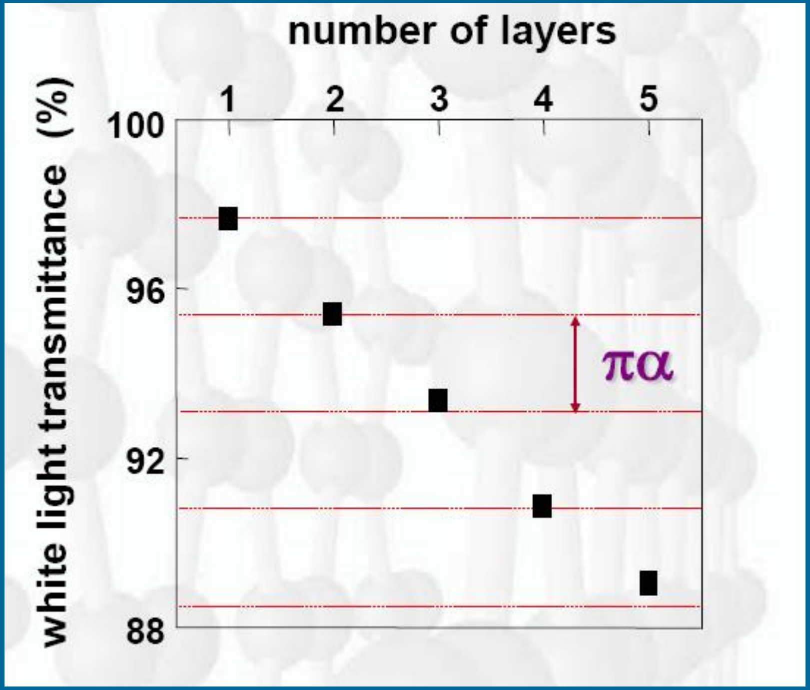


$$\pi\alpha = \pi\frac{e^2}{\hbar c} = 2{,}3\,\%$$

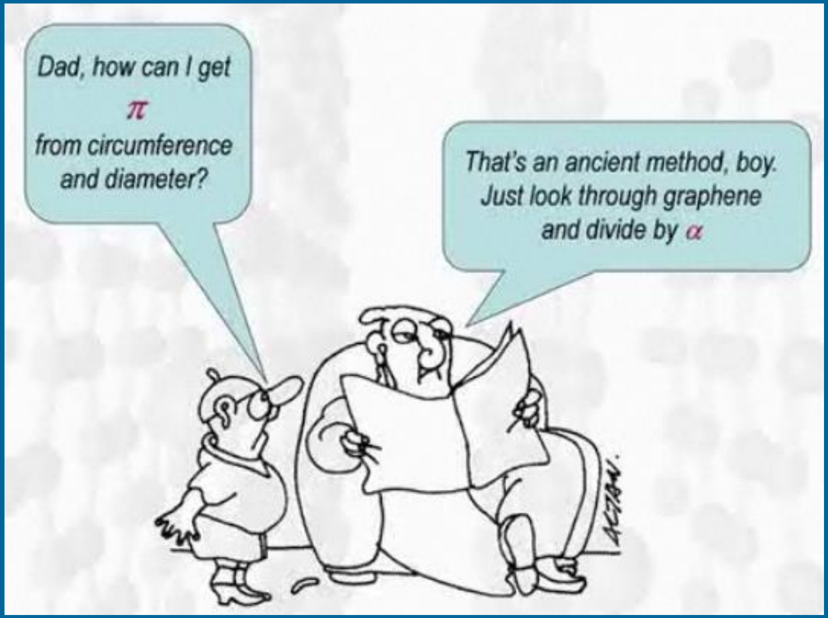
Nair et al., *Science* 2008;320:1308

Propriedades óticas do grafeno

Obtenção da constante de estrutura fina:

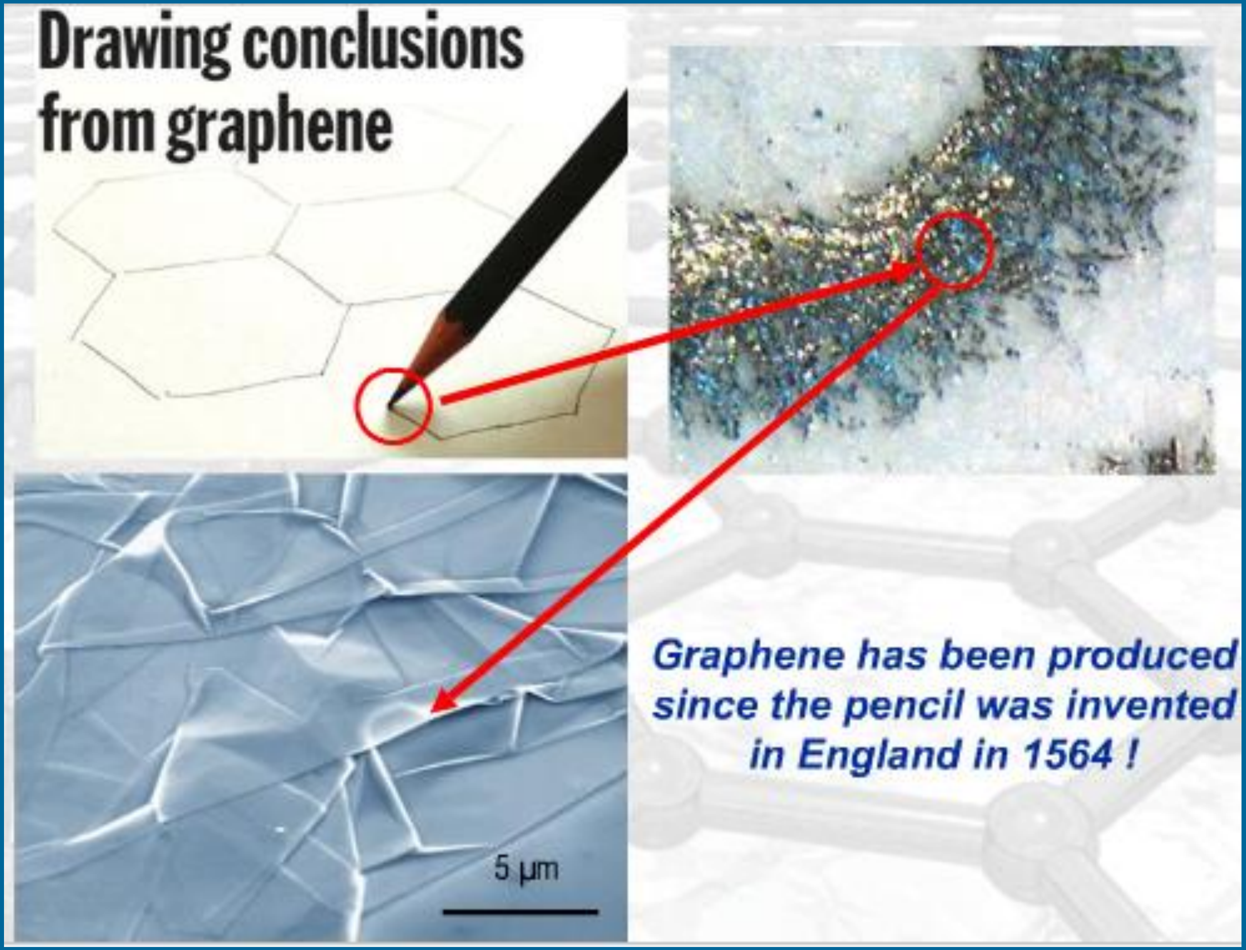


Nair et al., *Science* 2008;320:1308



http://www.iop.org/resources/videos/conference-videos/cmmp/page_45044.html

Produção de grafeno

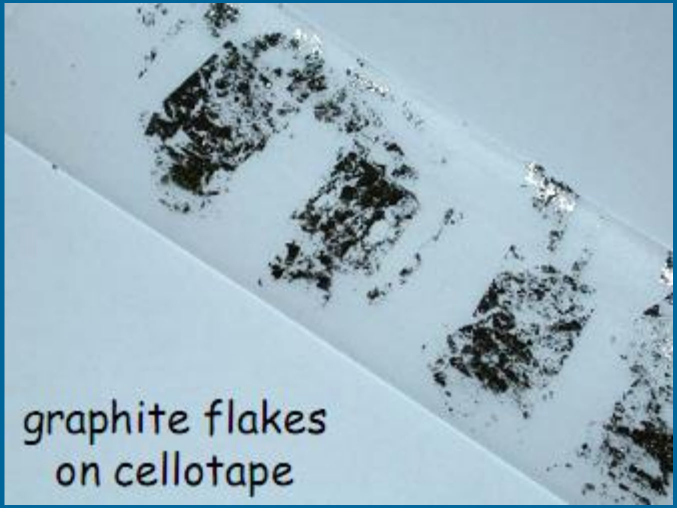


Castro Neto et al., *Physics World* 2006;19:33

Produção de grafeno

A técnica da fita adesiva (“Scotch tape”):

http://www.youtube.com/watch?v=rphiCdR68TE&feature=player_embedded#at=16



http://static.nobelprize.org/nobel_prizes/physics/laureates/2010/geim-lecture-slides.pdf

Produção de grafeno

A técnica da fita adesiva (“Scotch tape”):

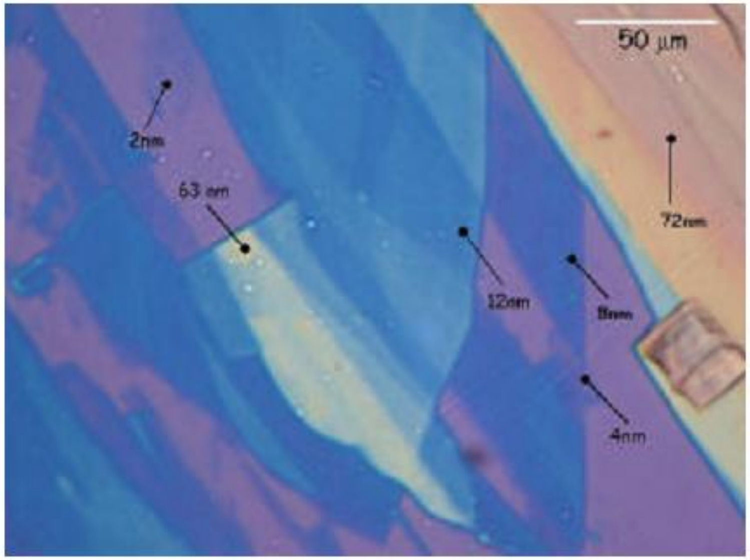
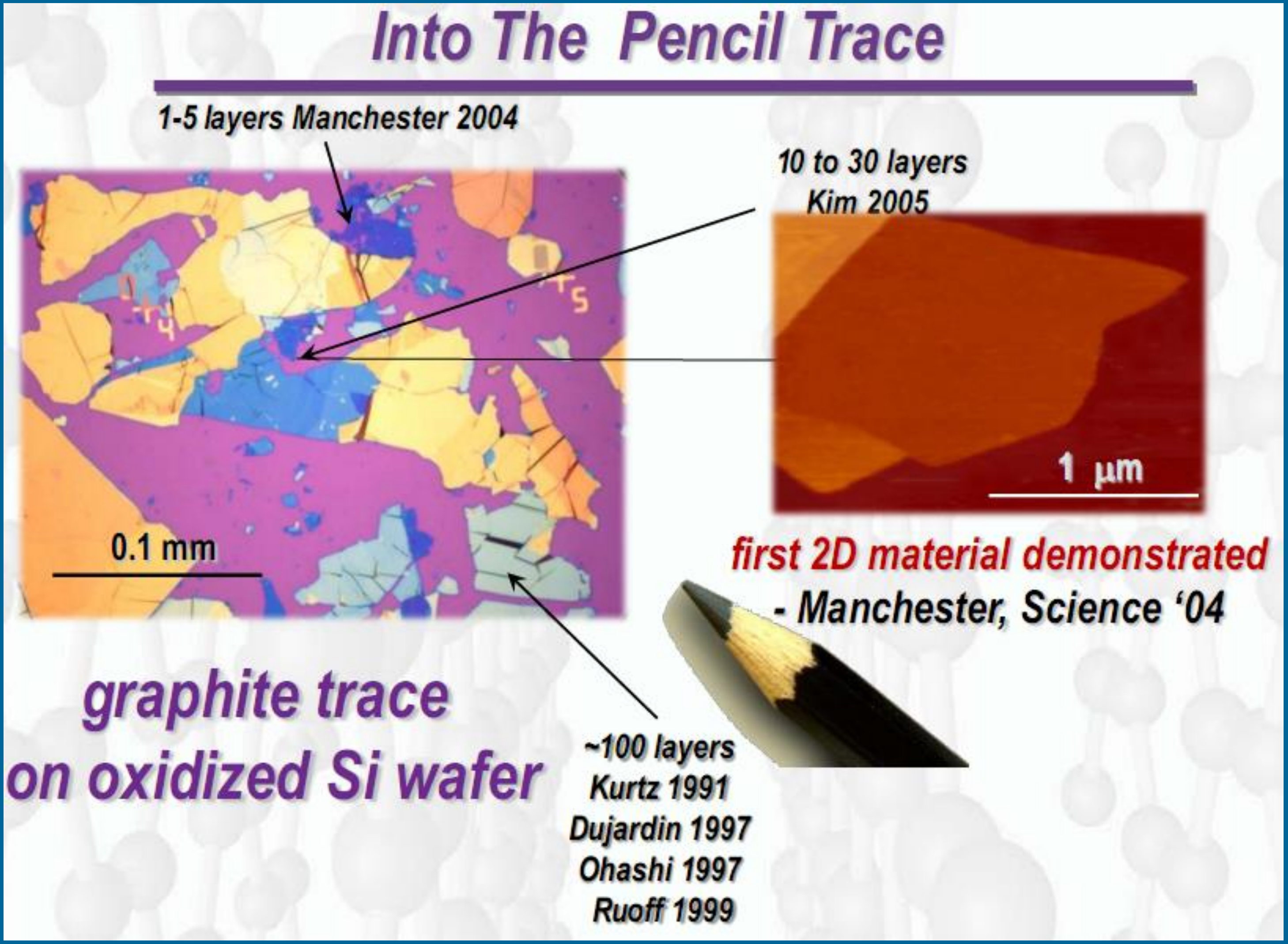


Figure S1. Optical photo in white light of graphitic films of various thickness *d*. The indicated values of *d* were measured by AFM. Note the area with $d \approx 2$ nm, which is barely visible in optics in the top-left corner.

Novoselov et al., *Science* 2004;306:666-669

Produção de grafeno



http://static.nobelprize.org/nobel_prizes/physics/laureates/2010/novoselov-lecture-slides.pdf

Produção de grafeno

Caracterização de grafeno – número de camadas:

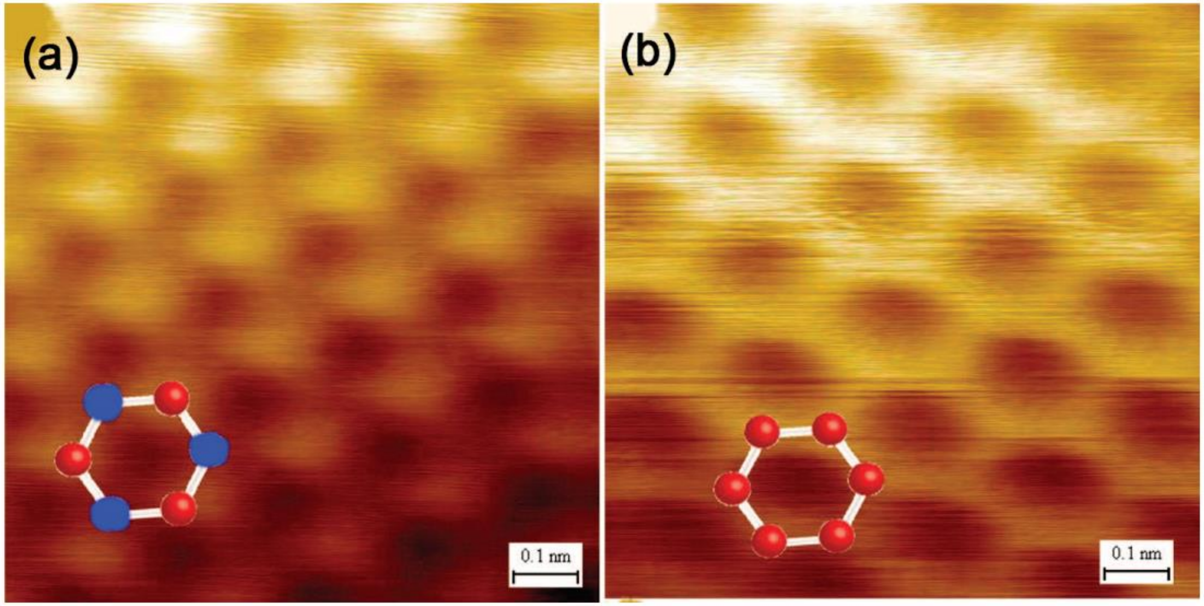


Figure 7. (a) STM image of graphite showing only the three carbons that eclipse a neighbor in the sheet directly below. (b) In contrast, all six carbons are equivalent and thus visible in mechanically exfoliated single-layer graphene. (Reprinted with permission from ref 79. Copyright 2007 PNAS.)

Allen et al., *Chem. Rev.* 2010;110:132

Produção de grafeno

Caracterização de grafeno – número de camadas:

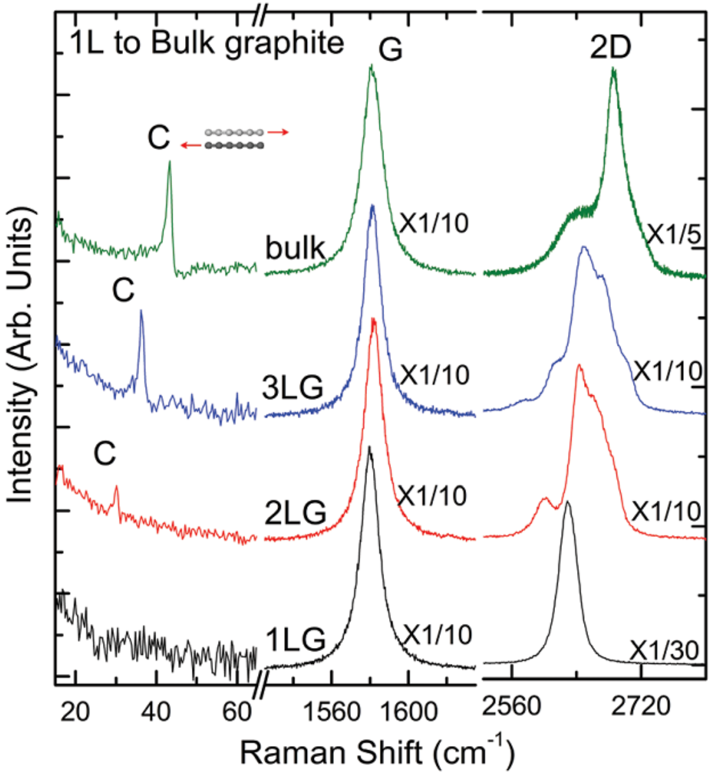


Fig. 16 Raman spectra of SLG (1LG), BLG (2LG), TLG (3LG), and bulk graphite measured at 633 nm. Adapted from ref. 204.

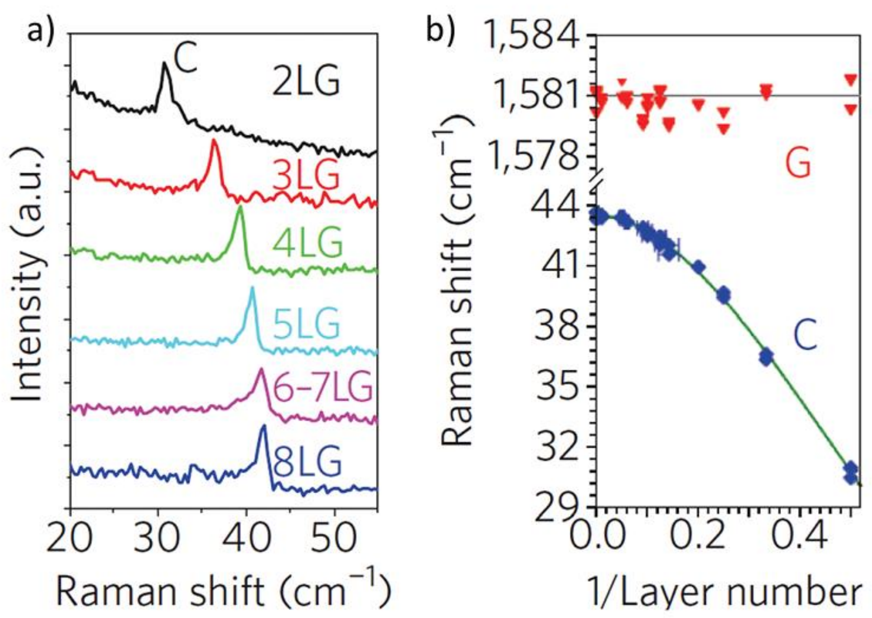


Fig. 17 (a) C peak as a function of number of layers. (b) Fitted C- and G-peak position as a function of inverse number of layers. Adapted from ref. 134.

Ferrari et al., *Nanoscale* 2015;7:4598

Produção de grafeno

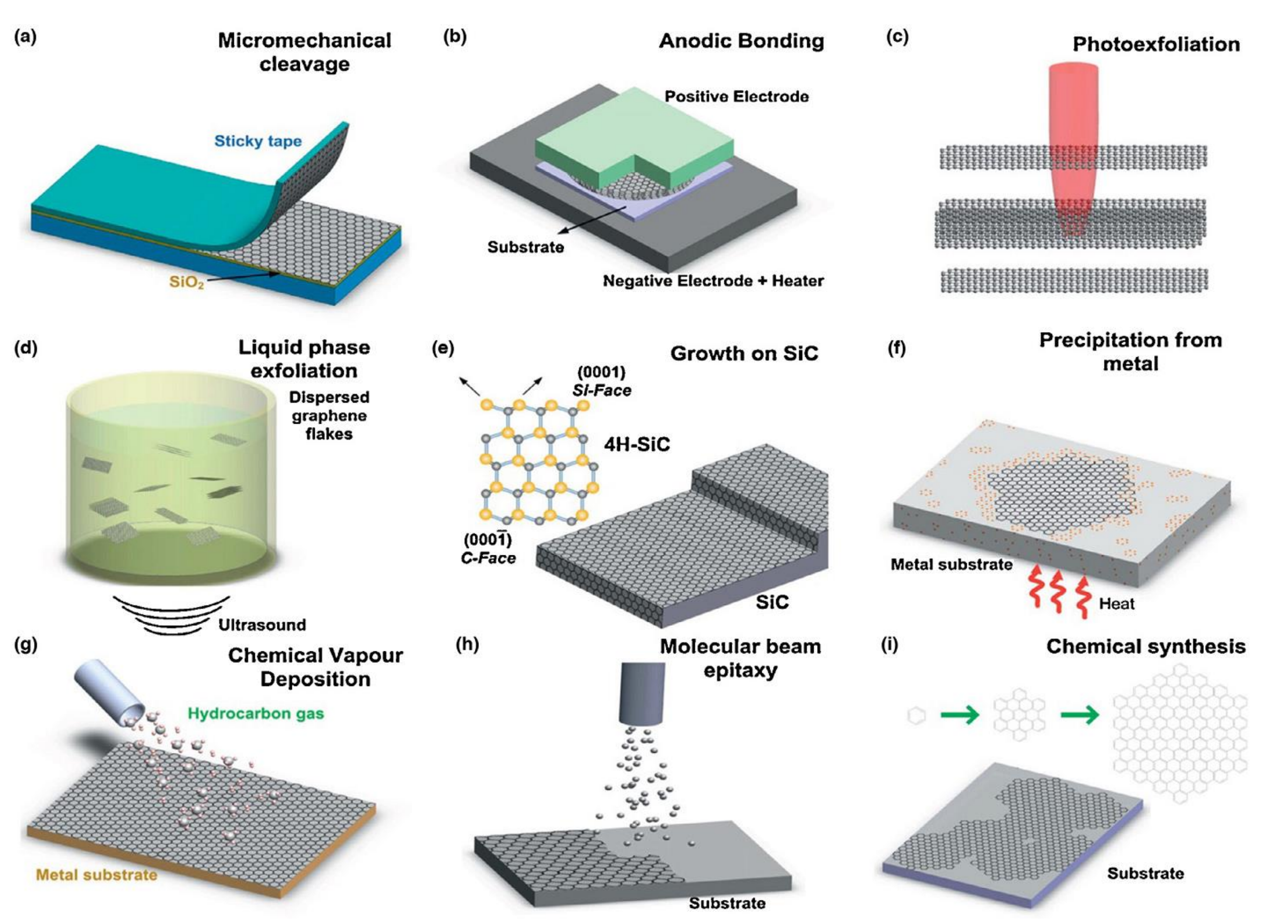


FIGURE 1

Schematic illustration of the main graphene production techniques. (a) Micromechanical cleavage. (b) Anodic bonding. (c) Photoexfoliation. (d) Liquid-phase exfoliation. (e) Growth on SiC. Gold and grey spheres represent Si and C atoms, respectively. At elevated T, Si atoms evaporate (arrows), leaving a carbon-rich surface that forms graphene sheets. (f) Segregation/precipitation from carbon containing metal substrate. (g) Chemical vapour deposition. (h) Molecular beam epitaxy. (i) Chemical synthesis using benzene as building block. Reproduced from Ref. [5] with permission from the Elsevier.

Zhong et al., *Mater. Today* 2014;18:73

Produção de grafeno

Table 2 State of the art (as of August 2014) of the main production approaches and foreseen applications

Method	Crystallites Size, μm	Sample Size, mm	μ	Applications
Micromechanical cleavage	1000	1	2×10^5 cm^2 V^{-1} s^{-1} 10^6 cm^2 V^{-1} s^{-1} (@T = 4 K) 2×10^4 cm^2 V^{-1} s^{-1} @RT	Fundamental research and proof of principle devices
LPE of graphite	0.01–1	0.1–1 (∞ as overlapping flakes)	100 cm^2 V^{-1} s^{-1} (for a layer of overlapping flakes) @RT	Inks, coatings, paints, batteries, supercaps, solar cells, fuel cells, composites, sensors, TCs, photonics, flexible electronics and optoelectronics, bio-applications
LPE of GO	>1	>1 (∞ as overlapping flakes)	1 cm^2 V^{-1} s^{-1} (for a layer of overlapping flakes) @RT	Inks, coatings, paints, batteries, supercap, solar cells, fuel cells, composites sensors, TCs, photonics, flexible electronics and optoelectronics, bio-applications
Growth on SiC	100	100 (6″)	6×10^6 cm^2 V^{-1} s^{-1} @T = 4 K	RF transistors other electronic devices
CVD	50 000	1000	6.5×10^4 cm^2 V^{-1} s^{-1} @T = 1.7 K 3×10^4 cm^2 V^{-1} s^{-1} @RT	Photonics, nanoelectronics, TCs, sensors, bio-applications, flexible electronics

Ferrari et al., *Nanoscale* 2015;7:4598

Produção de grafeno – esfoliação química

Síntese de óxido de grafeno:

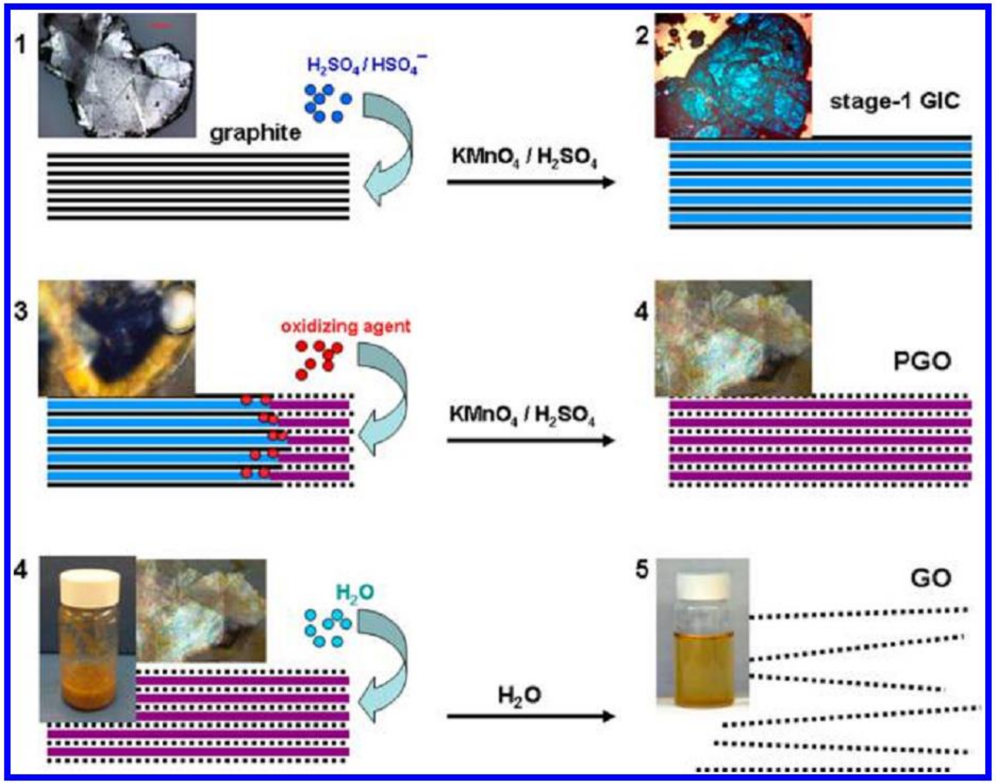
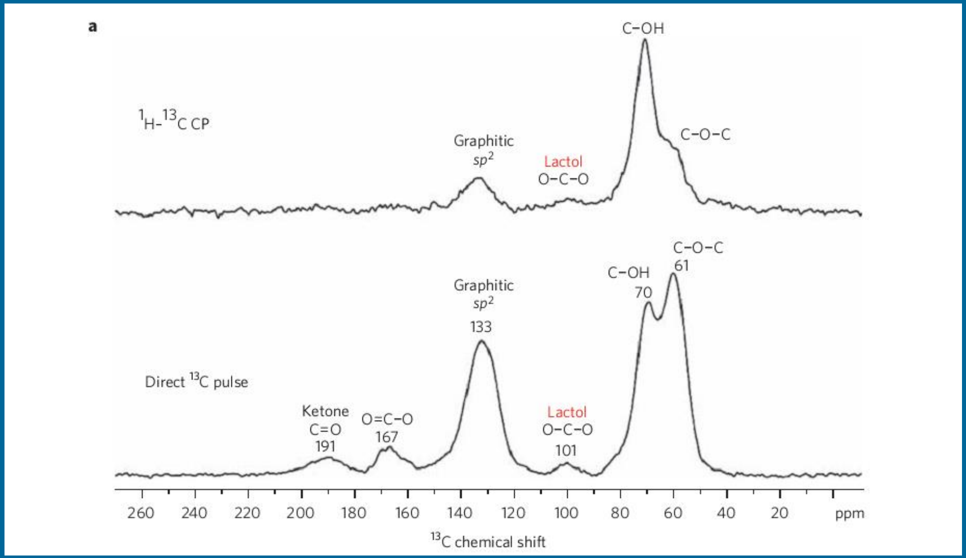


Figure 5. Schematics of conversion of bulk graphite into GO with corresponding micrographic images or sample appearances at each phase. The three steps signify formation of the two intermediate products (stage-1 GIC and PGO) and the final GO product. The solid black lines represent graphene layers; dotted black lines represent single layers of GO; wide blue lines represent H_2SO_4/HSO_4^- intercalant; wide purple lines represent a layer of the mixture of H_2SO_4/HSO_4^- intercalant with the reduced form of oxidizing agent.

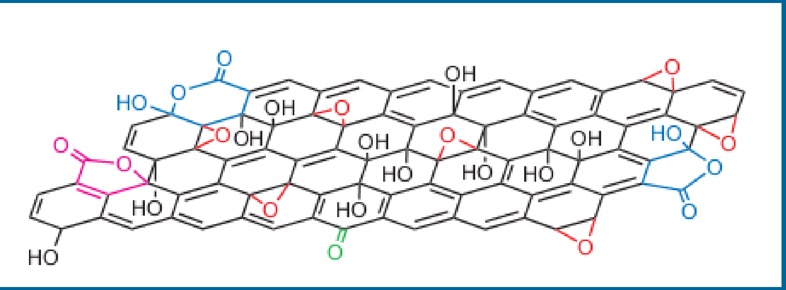
Dimiev & Tour, *ACS Nano* 2014;8:3060

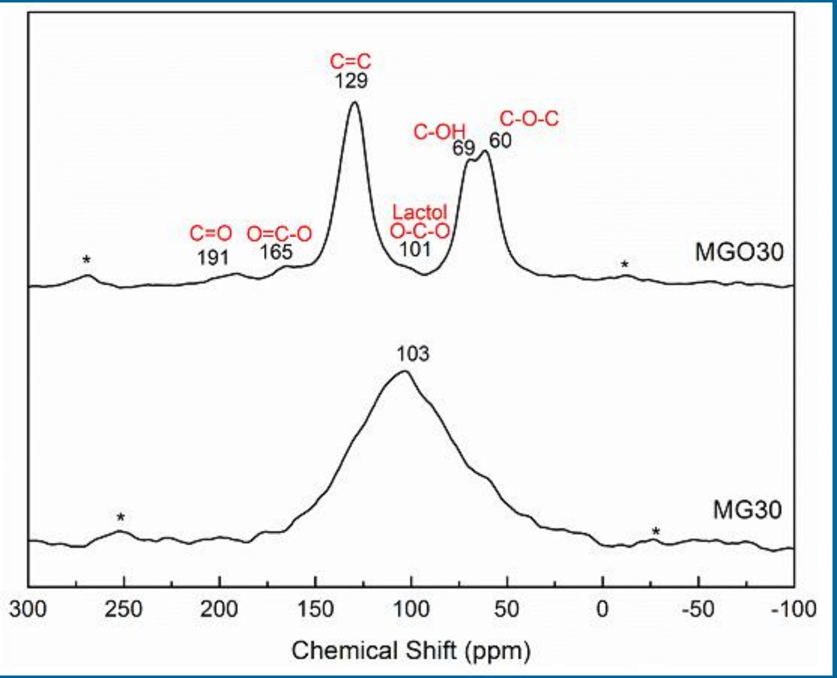
Óxido de grafeno

RMN de ^{13}C:



Gao et al., *Nature Chem.* 2009;1:403-408

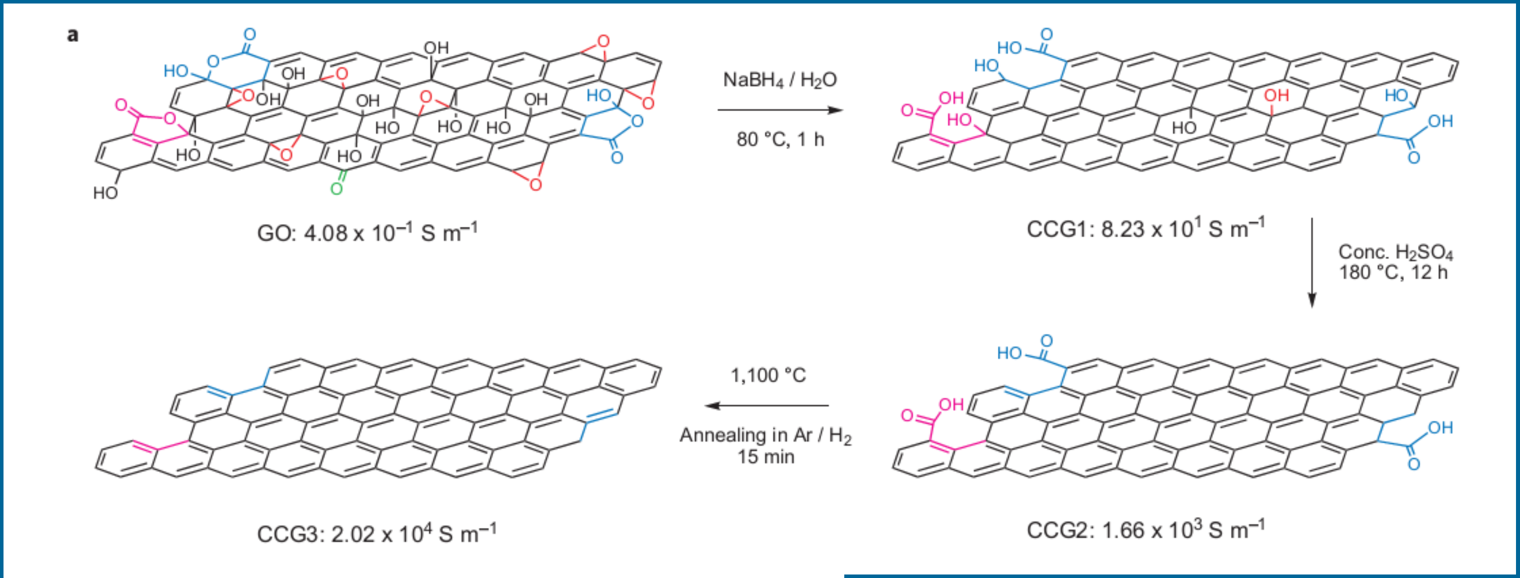


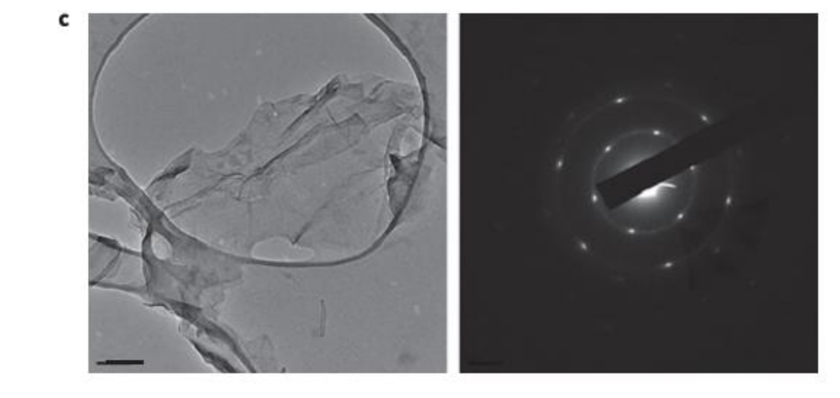


Freitas et al., *Carbon* 2016;98:496

Óxido de grafeno

Produção de grafeno – redução do óxido de grafeno:





Gao et al., *Nature Chem.* 2009;1:403-408

Óxido de grafeno

Fibras de óxido de grafeno:

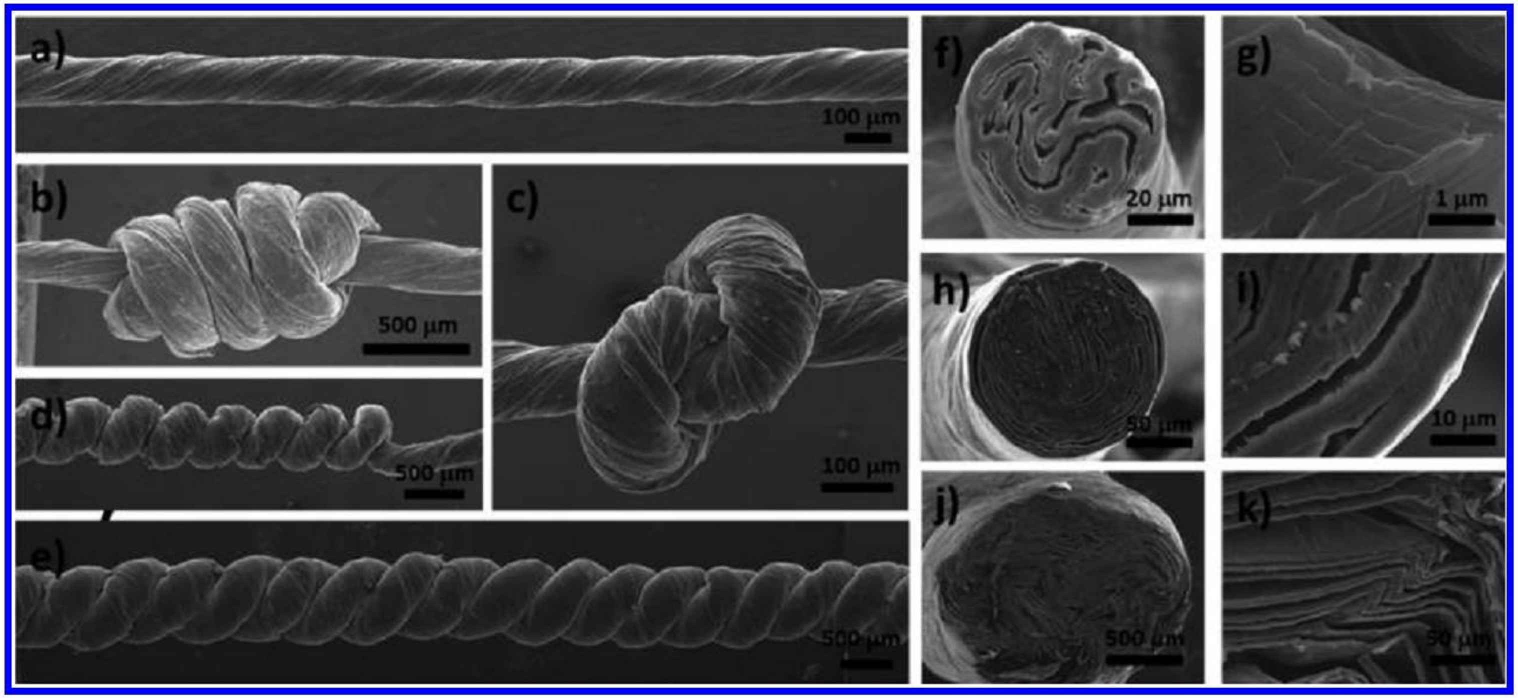


Figure 2. SEM images of GO fibers with different morphologies and knot architectures. (a) Typical dry-scrolled GO fiber; (b) quadruple overhand knot; (c) single knot; (d) self-coiled homochiral yarn; (e) neat two-ply yarn; (f) 60 μm diameter fiber made by mechanically scrolling a 0.74 μm thick GO sheet; (g) high-resolution image shows the layer-by-layer stacking within fibers; (h) cross section of a mechanically scrolled 150 μm diameter fiber; (i) zoom of the fiber cross section shown in (h); (j) cross section of a 1.1 mm diameter fiber made by manual scrolling; and (k) higher magnification image of (j) showing the formation of well-ordered areas of alternate stacks of GO sheets and voids.

Terrones et al., *ACS Nano* 2014;8:5959

Produção de grafeno – esfoliação química

Esfoliação em fase líquida:

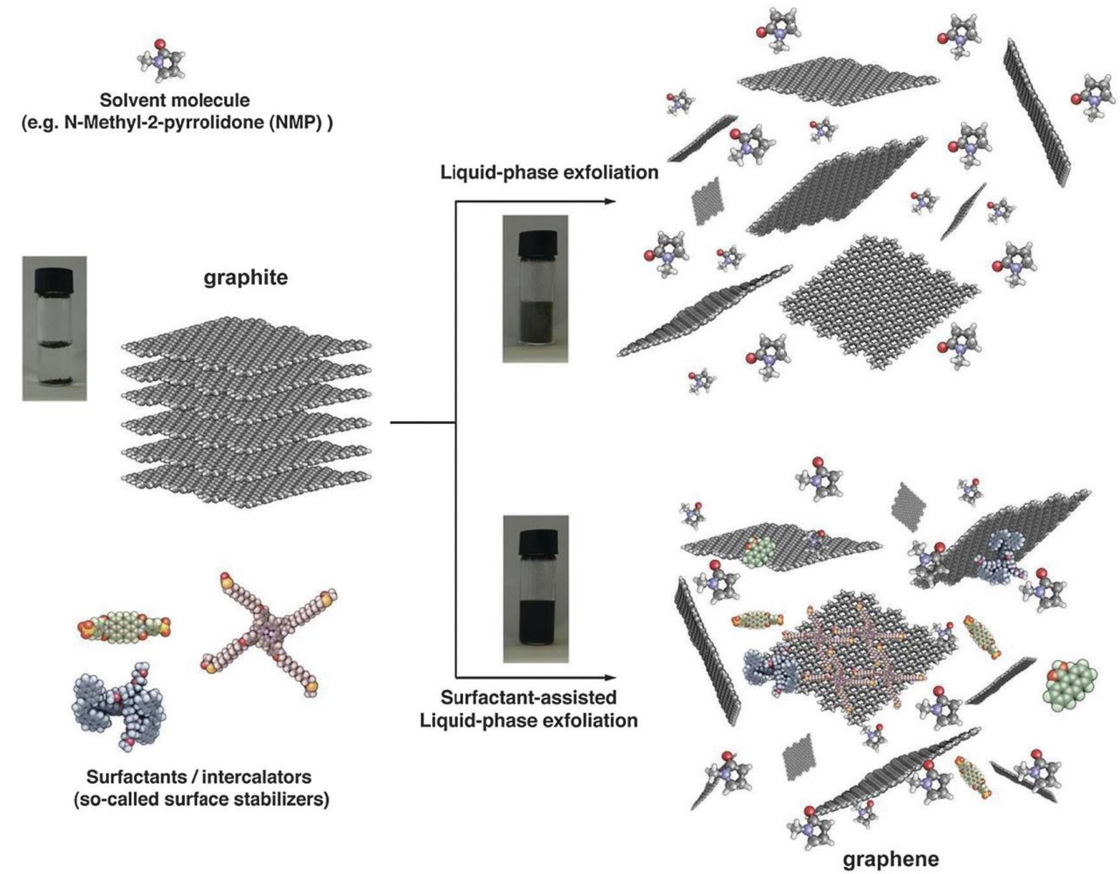
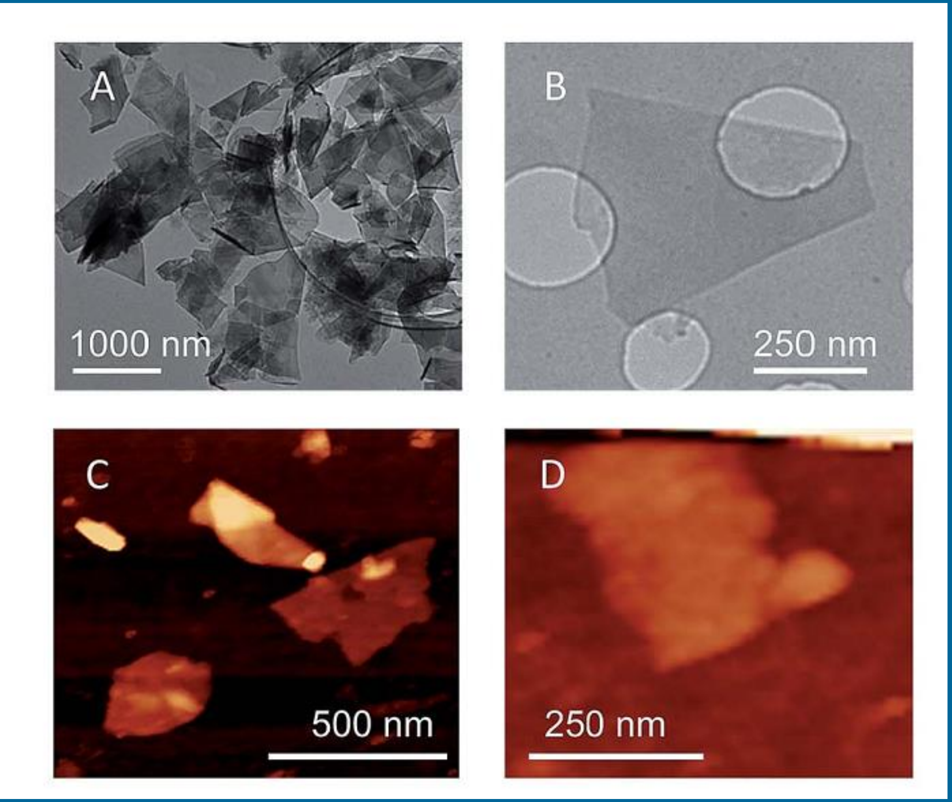


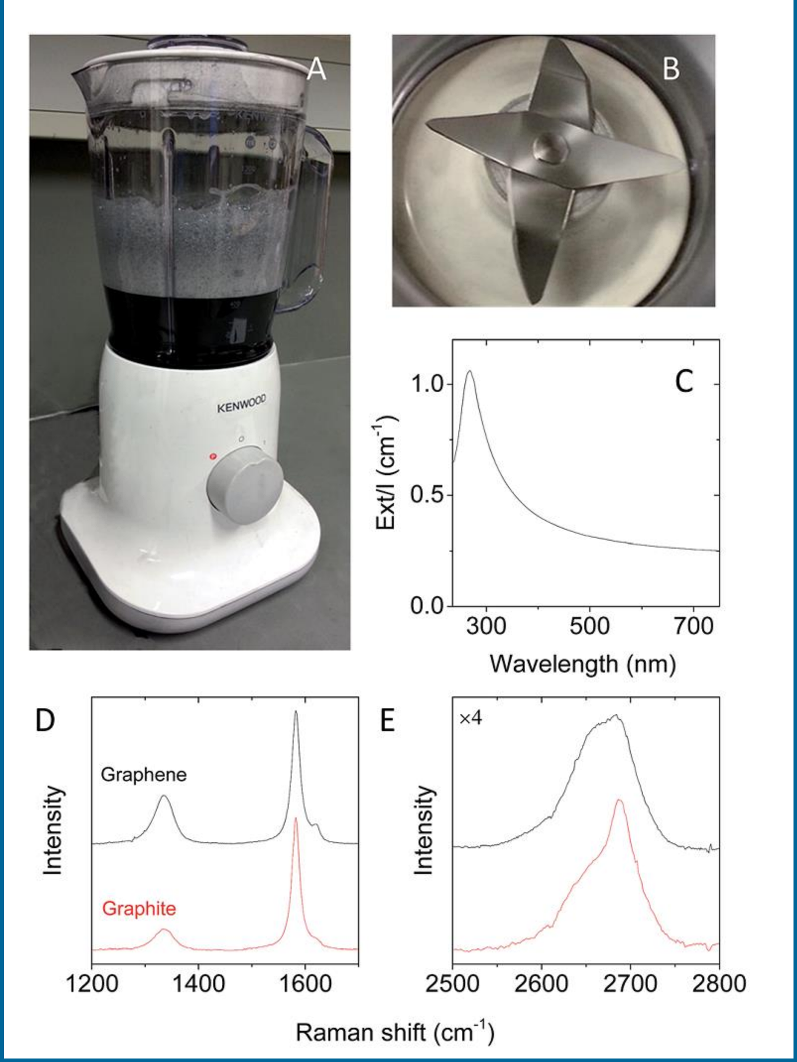
Fig. 1 Schematic representation of the liquid-phase exfoliation process of graphite in the absence (top-right) and presence (bottom-right) of surfactant molecules.

Ciesielski & Samori, *Chem. Soc. Rev.* 2014;43:381

Produção de grafeno – esfoliação química

Esfoliação em fase líquida:





Coleman et al., *Nanoscale* 2014;6:11810

Produção de grafeno

Deposição química em fase vapor (CVD):

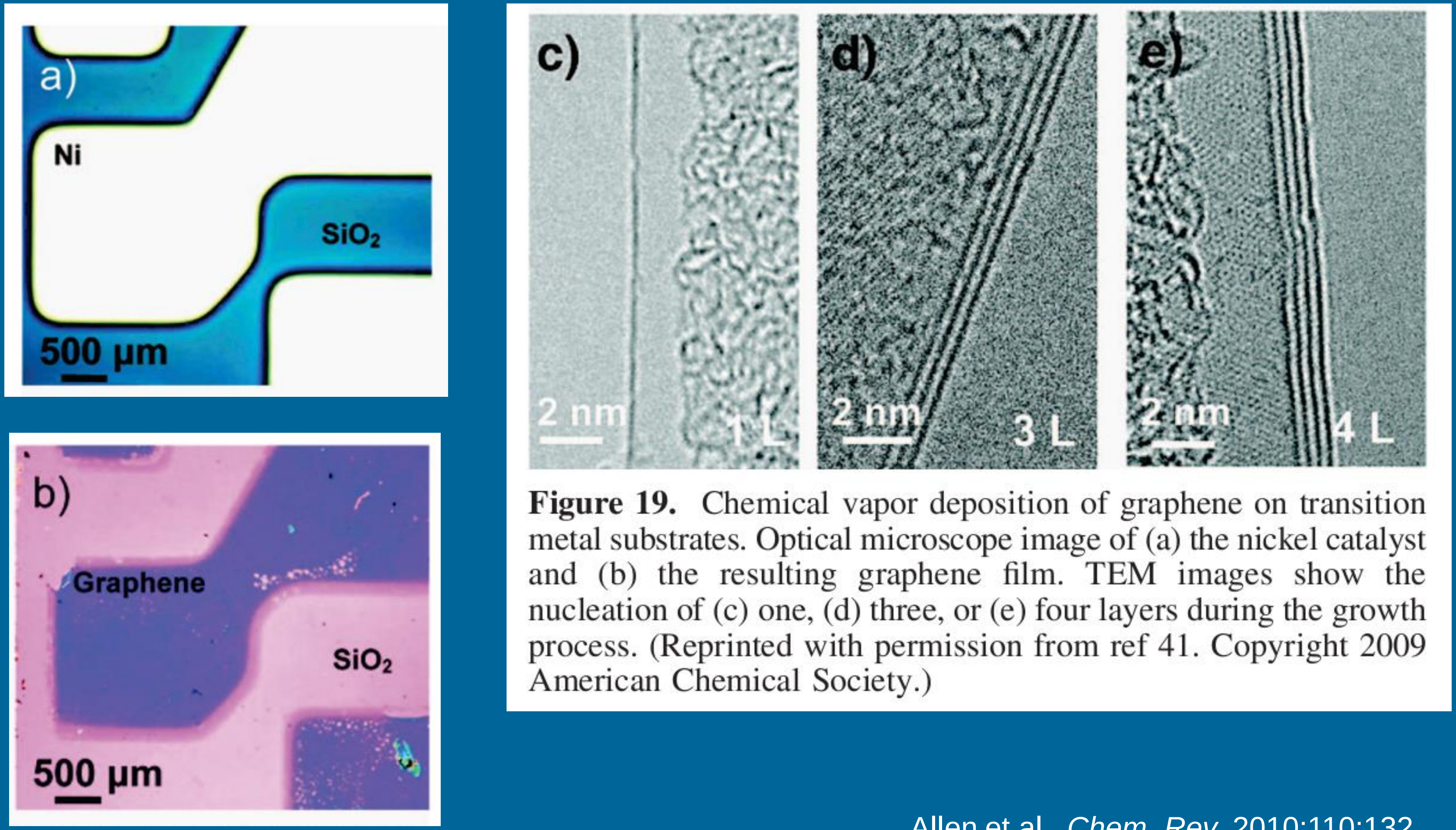


Figure 19. Chemical vapor deposition of graphene on transition metal substrates. Optical microscope image of (a) the nickel catalyst and (b) the resulting graphene film. TEM images show the nucleation of (c) one, (d) three, or (e) four layers during the growth process. (Reprinted with permission from ref 41. Copyright 2009 American Chemical Society.)

Allen et al., *Chem. Rev.* 2010;110:132

Produção de grafeno

Deposição química em fase vapor (CVD):

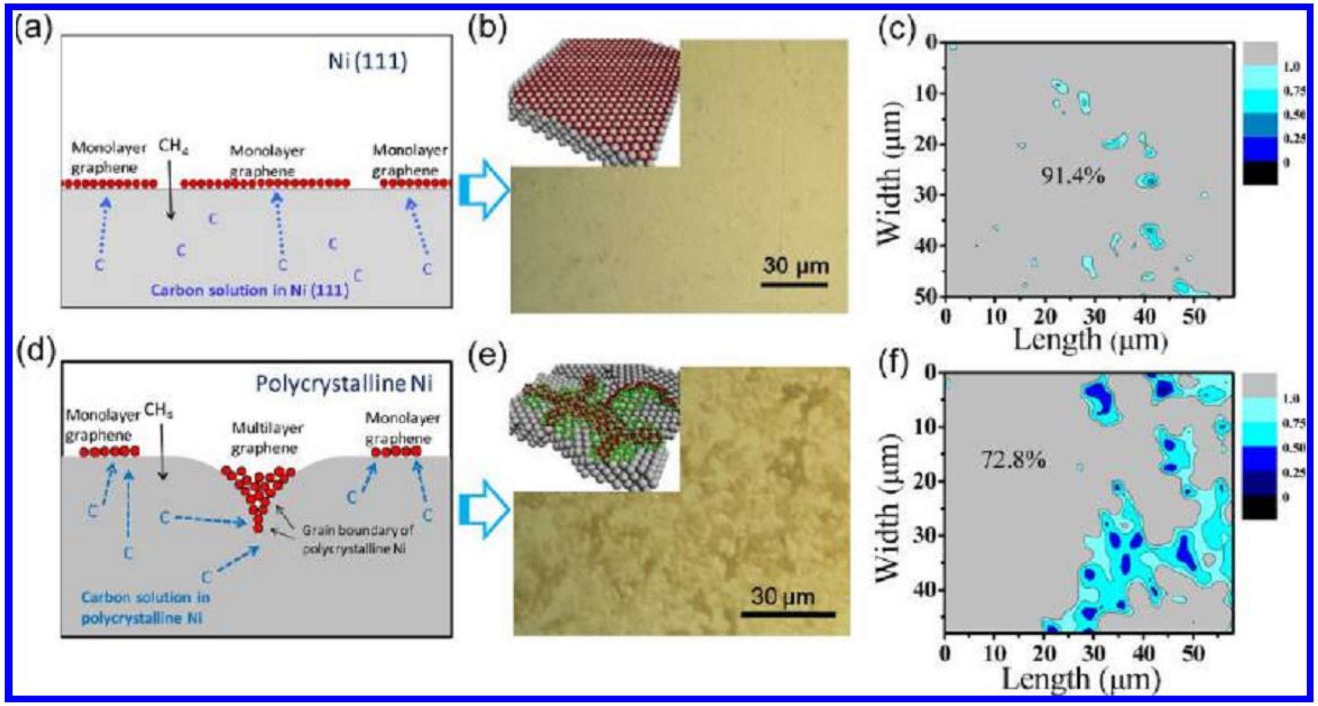
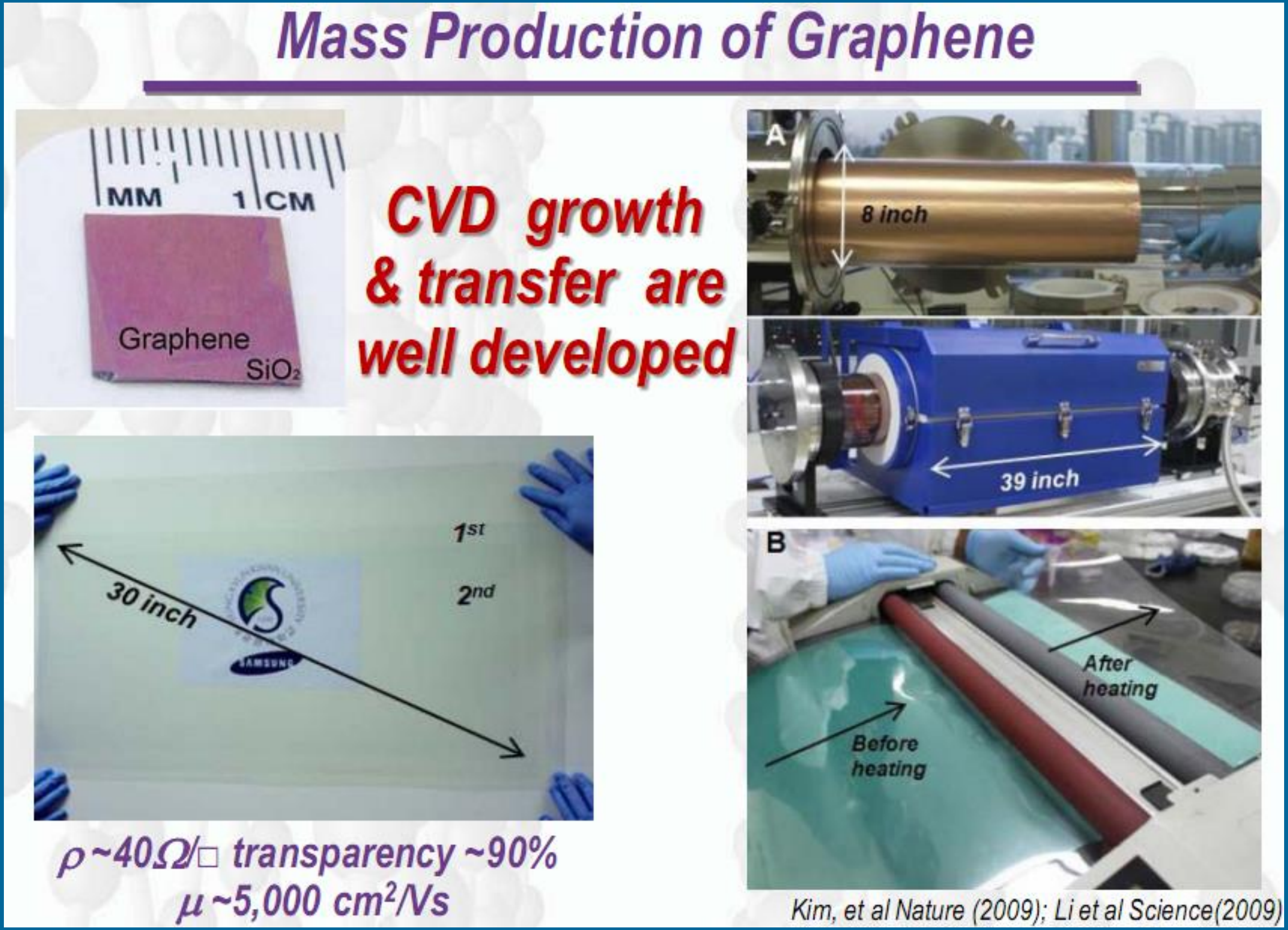


FIGURE 2. Schematic diagrams of graphene growth mechanism on Ni(111) (a) and polycrystalline Ni surface (d). Optical image of graphene grown on Ni(111) (b) and polycrystalline Ni (e). Maps of $I_{G'}/I_G$ of Raman spectra collected on the Ni(111) surface (c) and on the polycrystalline Ni surface (f) (Adapted with permission from ref 29. Copyright 2010 American Chemical Society).

Zhang et al., *Accounts Chem. Res.* 2013;10:2329

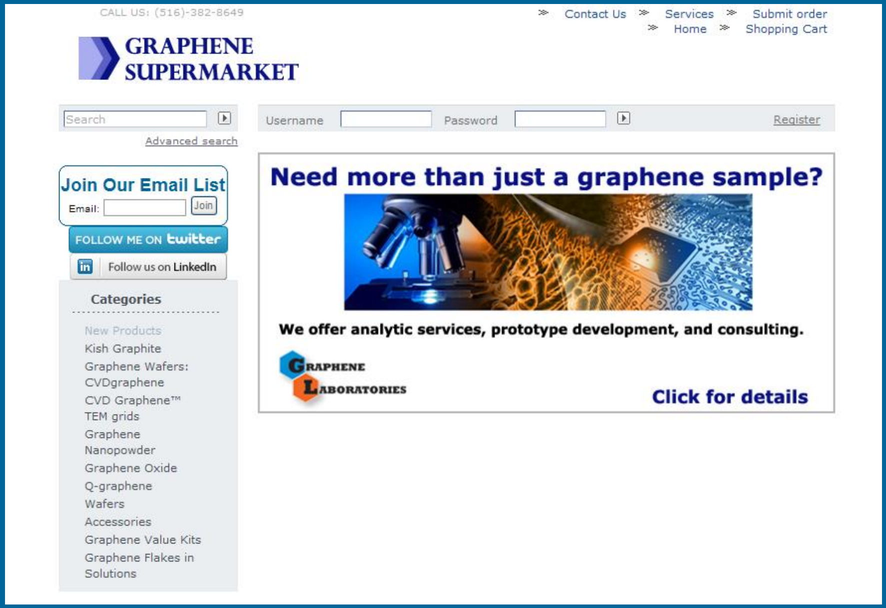
Produção de grafeno

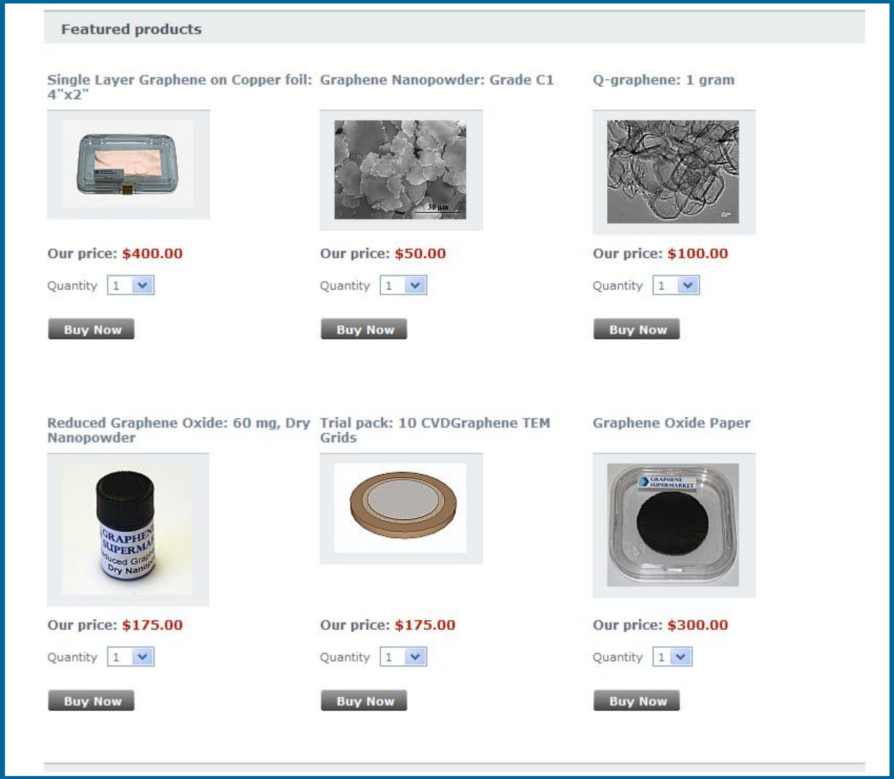


http://static.nobelprize.org/nobel_prizes/physics/laureates/2010/novoselov-lecture-slides.pdf

Produção de grafeno

Produção comercial:





https://graphene-supermarket.com/

Produção de grafeno

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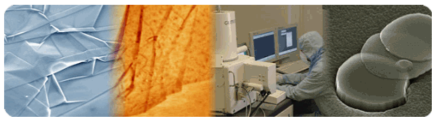


Welcome to Graphene Industries

Graphene Industries is the world's first supplier of the atomically thin, crystallographically perfect film of graphitic carbon, known as graphene.

We supply research institutions with development grade samples of graphene with lateral dimensions of the order of 100μm on silicon substrates, processed into devices such as Hall bar geometries, ultrasensitive gas sensors or suspended from metallic scaffolding for use as support films in electron microscopy applications. For a brief introduction to graphene take a look at our "what is graphene?" page.

If you are interested in working with graphene we have an online sample catalog of samples for sale.

News

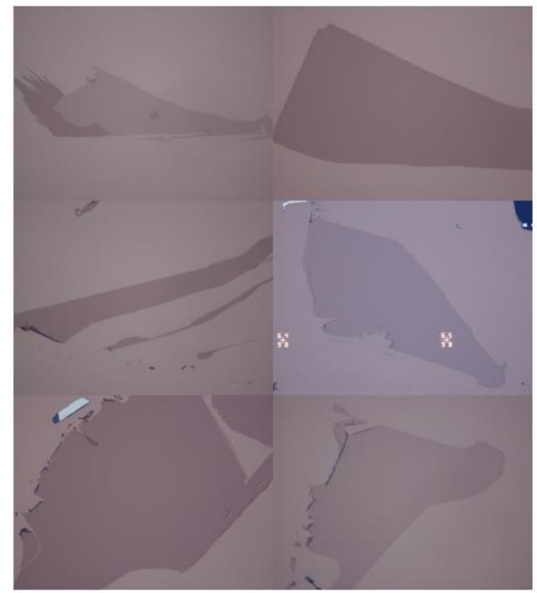
8-Dec-2010: **Kostya Novoselov** mentioned Graphene Industries in his Nobel Lecture.

5-Oct-2010: **Andre Geim** and **Kostya Novoselov** have won the 2010 Physics Nobel Prize for their discovery of graphene.

Sample: S5520

Sold

Flake Areas (μm^2)	1000, 20000 (bilayer), 1000 (bilayer), 80000, 25000 (bilayer), 3500
Substrate	90nm SiO_2 on n-doped 525μm Si
Price	£1900



PDF Datasheet

http://grapheneindustries.com

Produção de grafeno

Novos produtos:

COMPUTING

Flexible Touch Screen Made with Printed Graphene

Sheets of atom-thick carbon could make displays that are super fast.

MONDAY, JUNE 21, 2010 | BY NIDHI SUBBARAMAN

E-mail Audio » Print

See through: Researchers have created a flexible graphene sheet with silver electrodes printed on it (top) that can be used as a touch screen when connected to control software on a computer (bottom). Credit: Byung Hee Hong, SKKU.

Graphene, a sheet of carbon just one atom thick, has spectacular strength, flexibility, transparency, and electrical conductivity. Spurred on by its potential for application in new devices like touch screens and solar cells, researchers have been toying with ways to make large sheets of pure graphene, for example by shaving off atom-thin flakes and chemically dissolving chunks of graphite oxide. Yet in the thirty-some years since graphene's discovery, laboratory experiments have mainly yielded mere flecks of the stuff, and mass manufacture has seemed a long way away.

"The future of the field certainly isn't flaking off pencil shavings," says Michael Strano, a professor of chemical engineering at MIT. "The large-area production of monolayer graphene was a serious technological hurdle to advancing graphene technology."

http://www.technologyreview.com/computing/25633/?a=f

Samsung et al Make 40-inch Graphene Sheet, Physicist Says

Jan 25, 2011 13:18
Tetsuo Nozawa, Nikkei Electronics

Konstantin Sergeyevich Novoselov speaking in the interview conducted by Nikkei Electronics

Konstantin Sergeyevich Novoselov, who is a professor at the University of Manchester, School of Physics & Astronomy, and a 2010 Nobel Physics Prize winner, delivered a lecture at Graphene Workshop.

The workshop, which was organized by Japan's National Institute for Materials Science (NIMS), took place from Jan 17 to 18, 2011, in Tsukuba City, Japan.

In an interview conducted by Nikkei Electronics after the lecture, he said, "I am surprised by the wide application of graphene and the fact that it is being developed at a speed faster than expected."

Asked about the 30-inch (diagonal length: about 76cm) graphene sheet that was jointly announced by SungKyunKwan University of Korea and Samsung Electronics Co Ltd in June 2010, Novoselov said, "We are developing it in collaboration with Samsung and others. We obtained a sample of the graphene sheet from them, and we are using it for validations and experiments." Many Japanese researchers only half believed the announcement.

"I heard that they recently succeeded in making a 40-inch (diagonal length: about 102cm) or larger graphene sheet," he added.

http://techon.nikkeibp.co.jp/english/NEWS_EN/20110125/189014/

Outros materiais bidimensionais

http://static.nobelprize.org/nobel_prizes/physics/laureates/2010/novoselov-lecture-slides.pdf

Outros materiais bidimensionais

Two-dimensional atomic crystals

K. S. Novoselov*, D. Jiang*, F. Schedin*, T. J. Booth*, V. V. Khotkevich*, S. V. Morozov†, and A. K. Geim*‡

*Centre for Mesoscience and Nanotechnology and School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom; and †Institute for Microelectronics Technology, Chernogolovka 142432, Russia

Edited by T. Maurice Rice, Swiss Federal Institute of Technology, Zurich, Switzerland, and approved June 7, 2005 (received for review April 6, 2005)

We report free-standing atomic crystals that are strictly 2D and can be viewed as individual atomic planes pulled out of bulk crystals or as unrolled single-wall nanotubes. By using micromechanical cleavage, we have prepared and studied a variety of 2D crystals including single layers of boron nitride, graphite, several dichalcogenides, and complex oxides. These atomically thin sheets (essentially gigantic 2D molecules unprotected from the immediate environment) are stable under ambient conditions, exhibit high crystal quality, and are continuous on a macroscopic scale.

Novoselov et al., *Proc. Natl Acad. Sci. USA* 2005;102:10451

Outros materiais bidimensionais

Exemplos de materiais 2D:

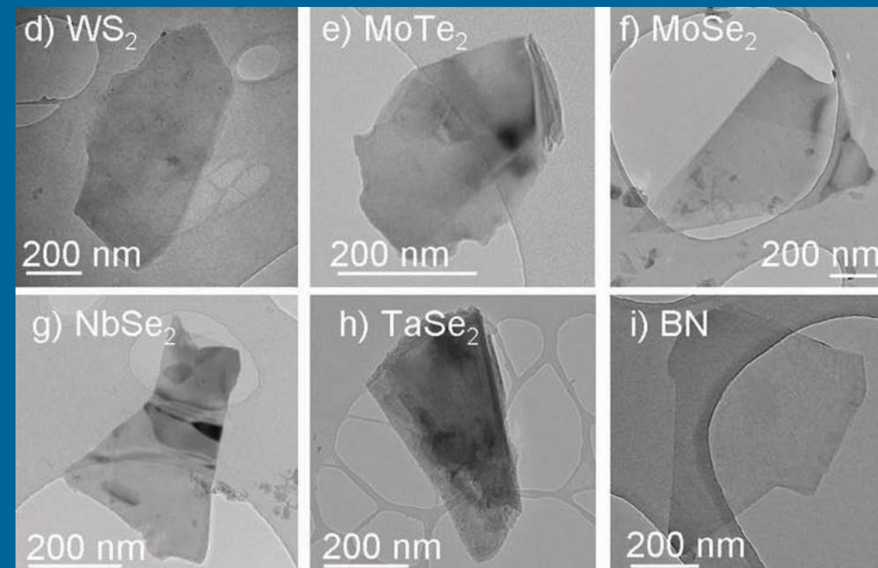
Graphene family	Graphene	hBN 'white graphene'	BCN	Fluorographene	Graphene oxide
2D chalcogenides	MoS_2, WS_2, $MoSe_2$, WSe_2	Semiconducting dichalcogenides: $MoTe_2$, WTe_2, ZrS_2, $ZrSe_2$ and so on	Metallic dichalcogenides: $NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$ and so on		
			Layered semiconductors: GaSe, GaTe, InSe, Bi_2Se_3 and so on		
2D oxides	Micas, BSCCO	MoO_3, WO_3	Perovskite-type: $LaNb_2O_7$, $(Ca,Sr)_2Nb_3O_{10}$, $Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$ and so on	Hydroxides: $Ni(OH)_2$, $Eu(OH)_2$ and so on	
	Layered Cu oxides	TiO_2, MnO_2, V_2O_5, TaO_3, RuO_2 and so on		Others	

Figure 2 | Current 2D library. Monolayers proved to be stable under ambient conditions (room temperature in air) are shaded blue; those probably stable in air are shaded green; and those unstable in air but that may be stable in inert atmosphere are shaded pink. Grey shading indicates 3D compounds that have been successfully exfoliated down to monolayers, as is clear from atomic force microscopy, for example, but for which there is little further information. The data given are summarized from refs 6–11, 42 and 55. We note that, after intercalation and exfoliation, the oxides and hydroxides may exhibit stoichiometry different from their 3D parents (for example, TiO_2 exfoliates into a stoichiometric monolayer of $Ti_{0.87}O_2$; ref. 8). 'Others' indicates that many other 2D crystals—including borides, carbides, nitrides and so on—have probably been[7–11] or can be isolated. BCN, boron carbon nitride.

Geim & Grigorieva, *Nature* 2013;499:419

Outros materiais bidimensionais

Esfoliação em fase líquida:



Coleman et al., *Adv. Mater.* 2011;23:3944

Outros materiais bidimensionais

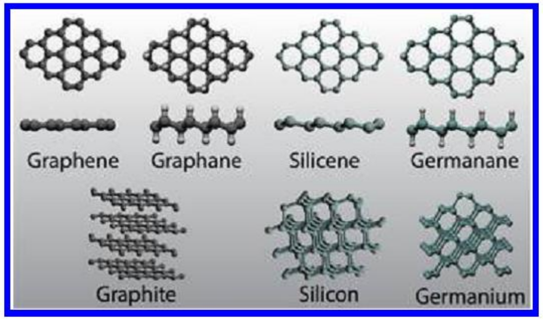


Figure 2. The growing family of Group IV monolayers. Generating group IV layered compounds has garnered significant interest for potential technological value in the semiconducting industry. The latest of these new materials is germanane, developed recently by Biano *et al.*

TABLE 2. Electronic Properties of Group IV (C, Si, Ge) Two-Dimensional Nanomaterials

	Band Gap [eV]	atomic puckering	mobility [cm^2/(V s)]	classification
Graphene	0 eV	0.00 Å	~200,000	Semimetal[19]
Graphane	3.6–5.4 eV	0.46 Å	-	Insulator[8]
Silicene	0.0 eV	0.44–0.72 Å	$\sim 10^5$	Semimetal[8]
Germanane	1.53–2.4 eV	0.63–0.73 Å	18,195	Direct-Gap Semiconductor[11]

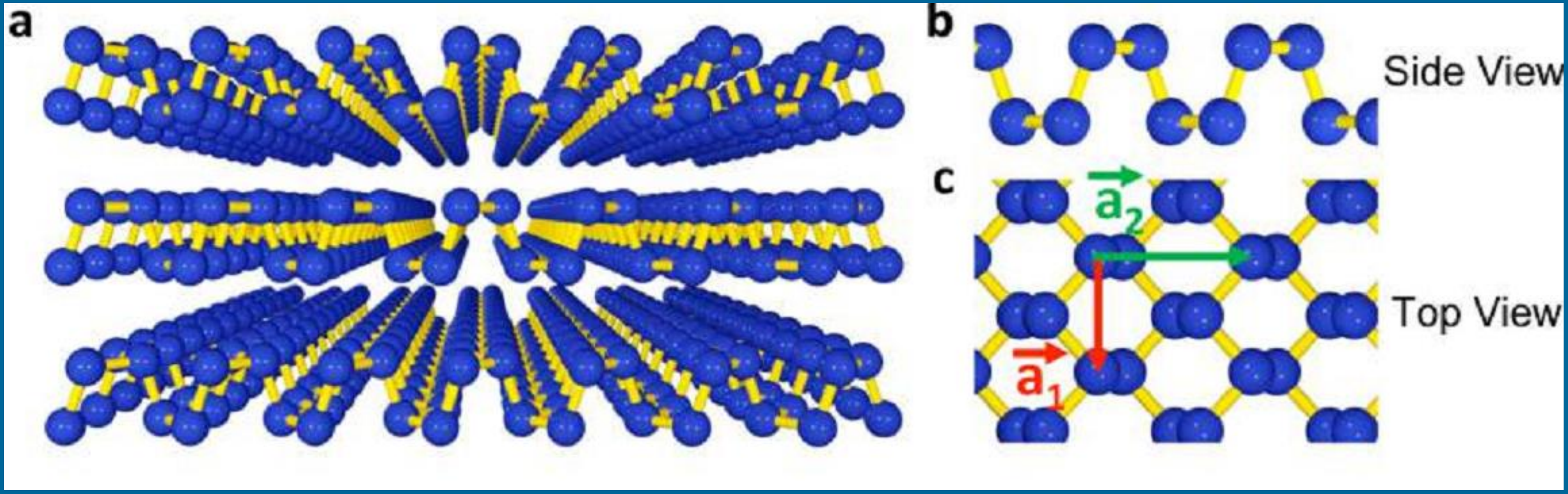
Koski & Cui, *ACS Nano* 2013;7:3739

Outros materiais bidimensionais

Phosphorene: An Unexplored 2D Semiconductor with a High Hole Mobility

Han Liu,[†,‡] Adam T. Neal,[†,‡] Zhen Zhu,[§] Zhe Luo,[‡,⊥] Xianfan Xu,[‡,⊥] David Tománek,[§] and Peide D. Ye[†,‡,*]

[†]School of Electrical and Computer Engineering and [‡]Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, United States, [§]Physics and Astronomy Department, Michigan State University, East Lansing, Michigan 48824, United States, and [⊥]School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907, United States



Liu et al., *ACS Nano* 2014;8:4033

Outros materiais bidimensionais

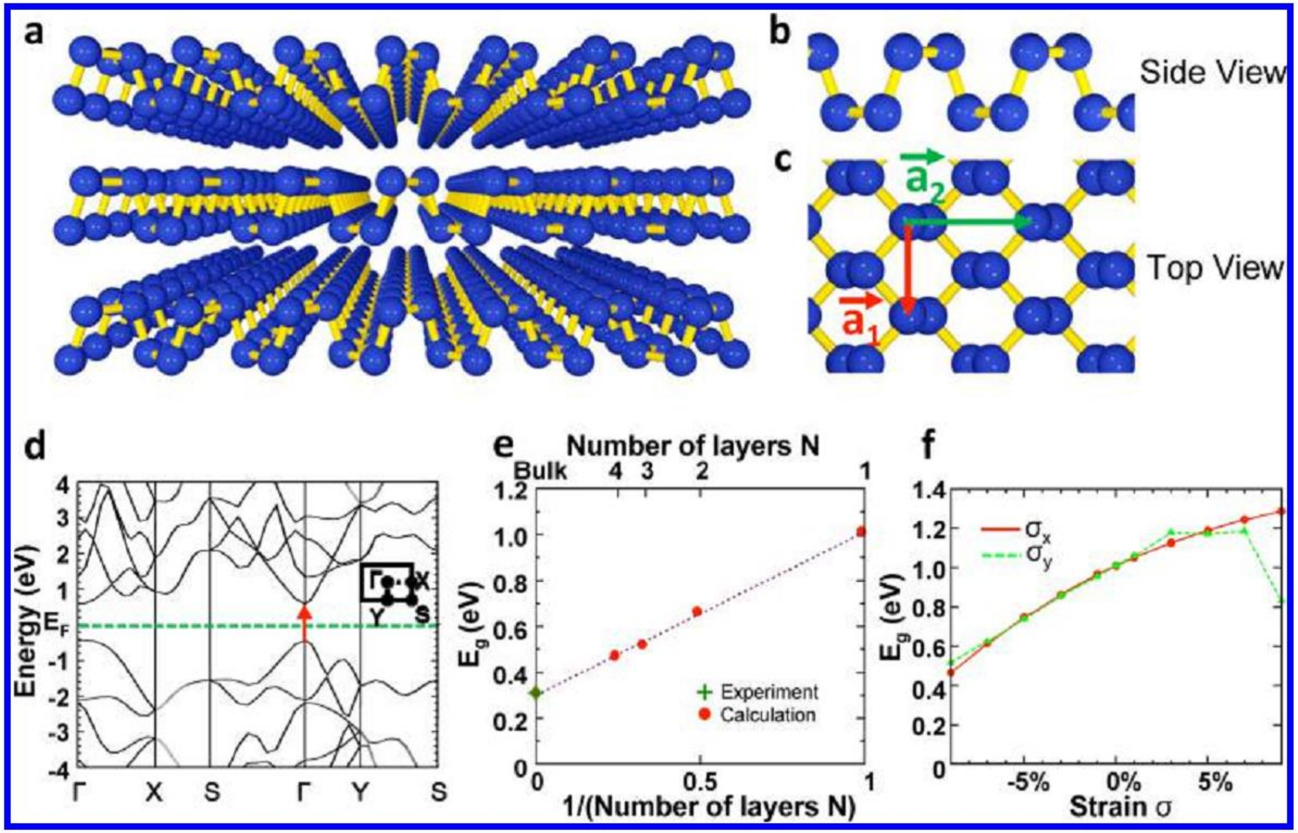


Figure 1. Crystal structure and band structure of few-layer phosphorene. (a) Perspective side view of few-layer phosphorene. (b,c) Side and top views of few-layer phosphorene. (d) DFT-HSE06 band structure of a phosphorene monolayer. (e,f) DFT-HSE06 results for the dependence of the energy gap in few-layer phosphorene on (e) the number of layers and (f) the strain along the *x*- and *y*-direction within a monolayer. The observed band gap value in the bulk is marked by a cross in (e).

Liu et al., *ACS Nano* 2014;8:4033

Outros materiais bidimensionais

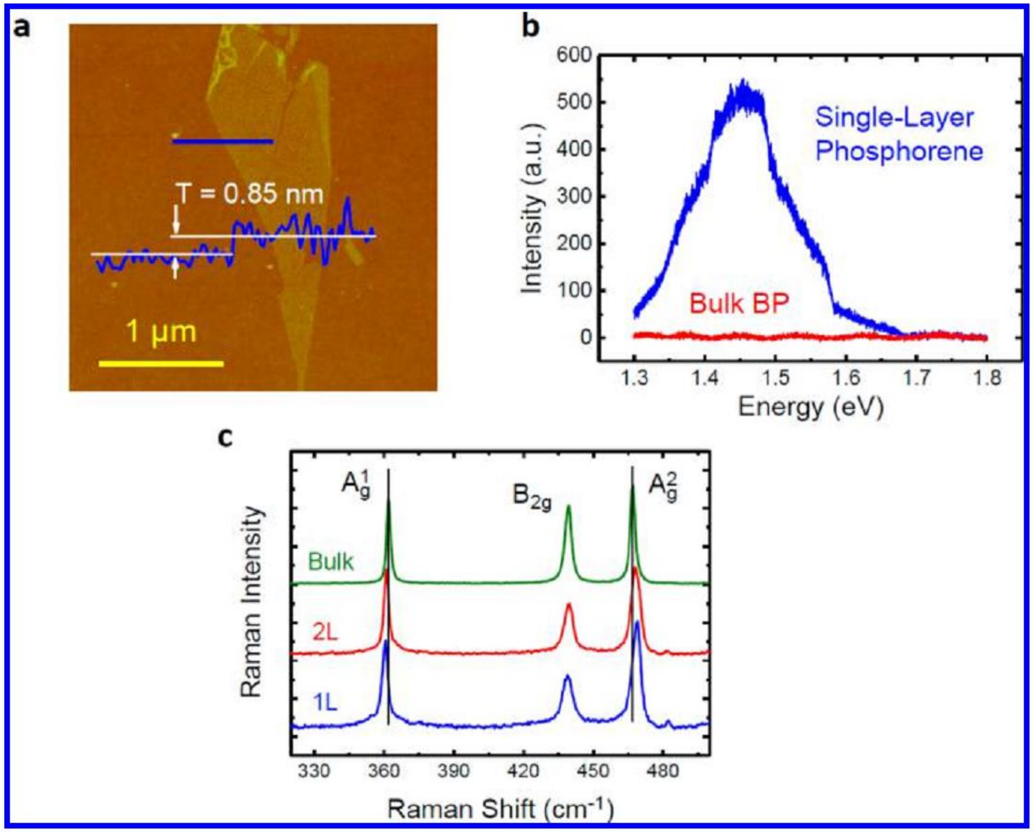


Figure 2. Material characterizations of single-layer and few-layer phosphorene. (a) Atomic force microscopy image of a single-layer phosphorene crystal with the measured thickness of ≈0.85 nm. (b) Photoluminescence spectra for single-layer phosphorene and bulk black phosphorus samples on a 300 nm SiO_2/Si substrate, showing a pronounced PL signal around 1.45 eV. To prevent the single-layer phosphorene reacting with the environment, it is covered by PMMA layer during experiments. (c) Raman spectra of single-layer and bilayer phosphorene and bulk black phosphorus films.

Liu et al., *ACS Nano* 2014;8:4033

Outros materiais bidimensionais

Heteroestruturas construídas a partir de materiais 2D:

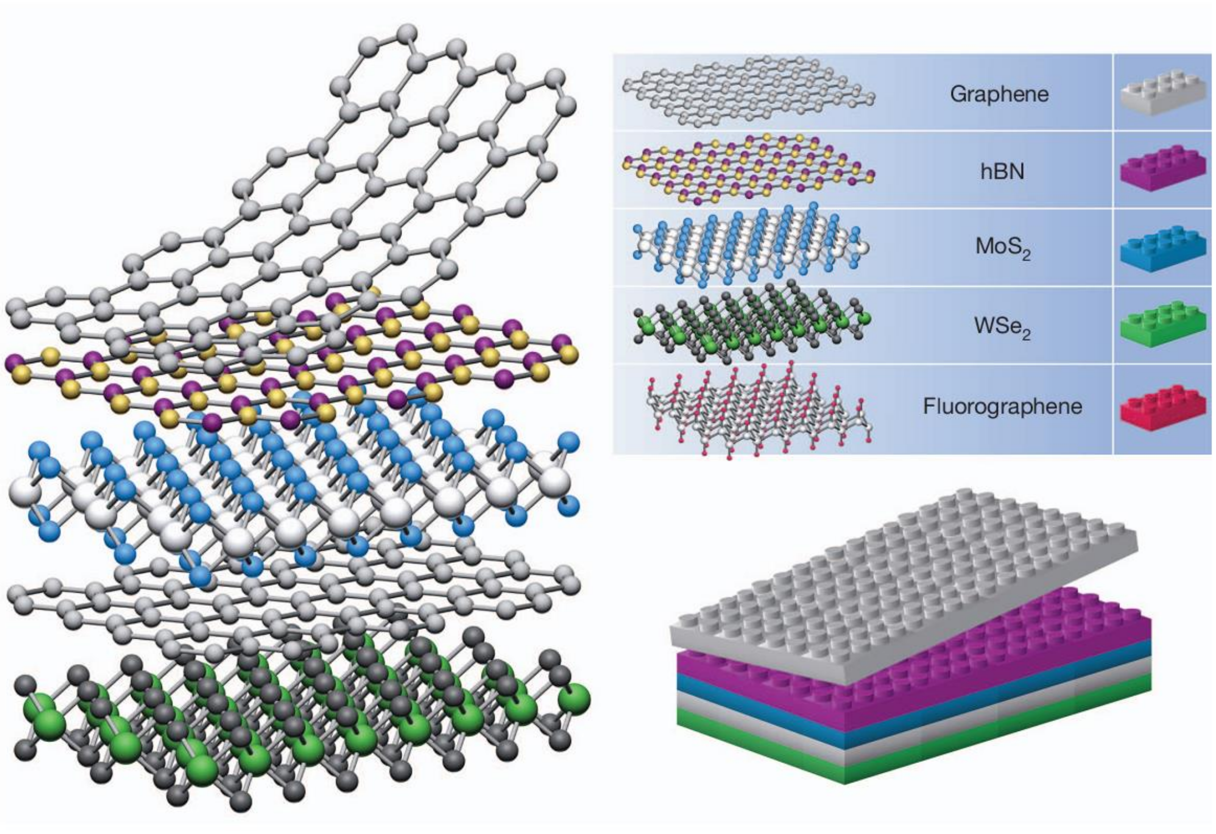


Figure 1 | Building van der Waals heterostructures. If one considers 2D crystals to be analogous to Lego blocks (right panel), the construction of a huge variety of layered structures becomes possible. Conceptually, this atomic-scale Lego resembles molecular beam epitaxy but employs different 'construction' rules and a distinct set of materials.

Geim & Grigorieva, *Nature* 2013;499:419

Outros materiais bidimensionais

Heteroestruturas construídas a partir de materiais 2D:

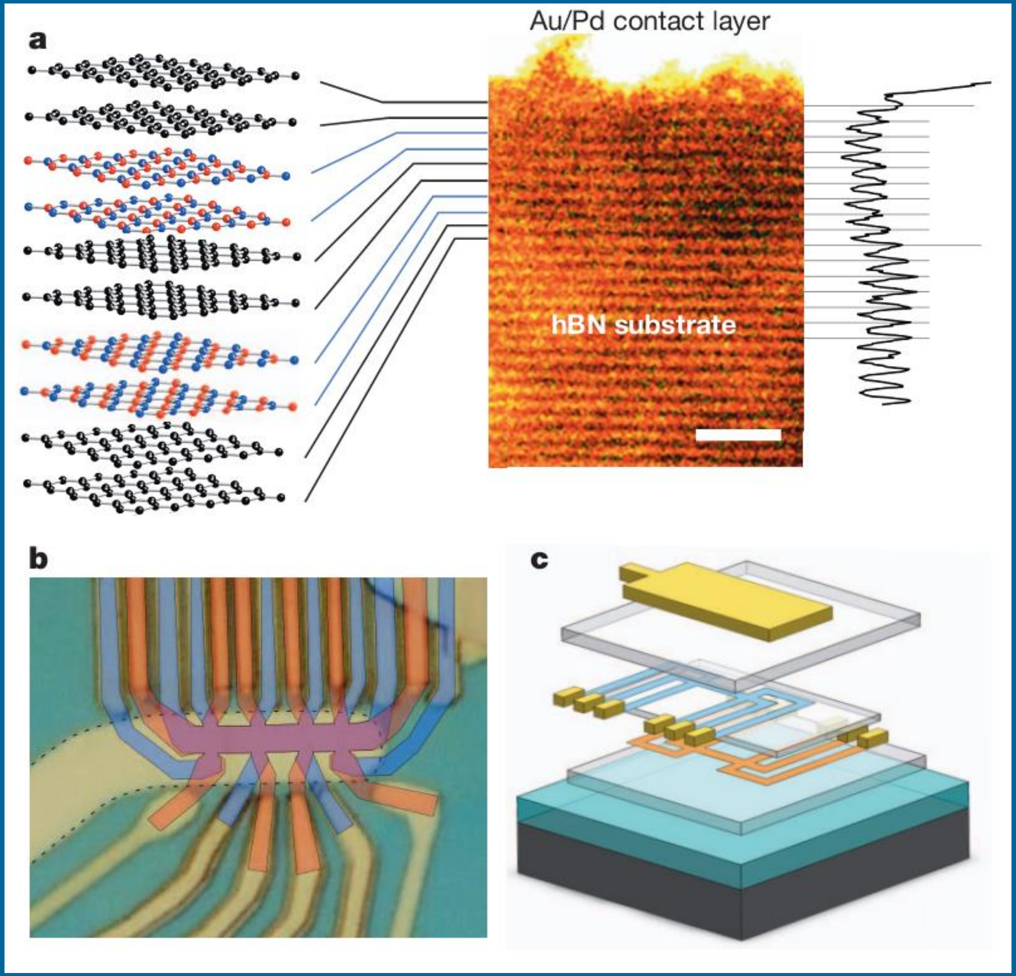


Figure 3 | State-of-the-art van der Waals structures and devices.
a, Graphene–hBN superlattice consisting of six stacked bilayers. On the right its cross-section and intensity profile as seen by scanning transmission electron microscopy are shown; on the left is a schematic view of the layer sequence. The topmost hBN bilayer is not visible, being merged with the metallic contact. Scale bar, 2 nm. (Adapted from ref. 16.) **b**, **c**, Double-layer graphene heterostructures[18]. An optical image of a working device (**b**) and its schematics in matching colours (**c**). Two graphene Hall bars are accurately aligned, separated by a trilayer hBN crystal and encapsulated between relatively thick hBN crystals (hBN is shown in **c** as semitransparent slabs). The entire heterostructure is placed on top of an oxidized Si wafer (SiO_2 is in turquoise). The colours in **b** indicate the top (blue) and bottom (orange) Hall bars and their overlapping region (violet). The graphene areas are invisible in the final device image because of the top Au gate outlined by dashes. The scale is given by the width of the Hall bars, 1.5 µm.

Geim & Grigorieva, *Nature* 2013;499:419

Aplicações do grafeno

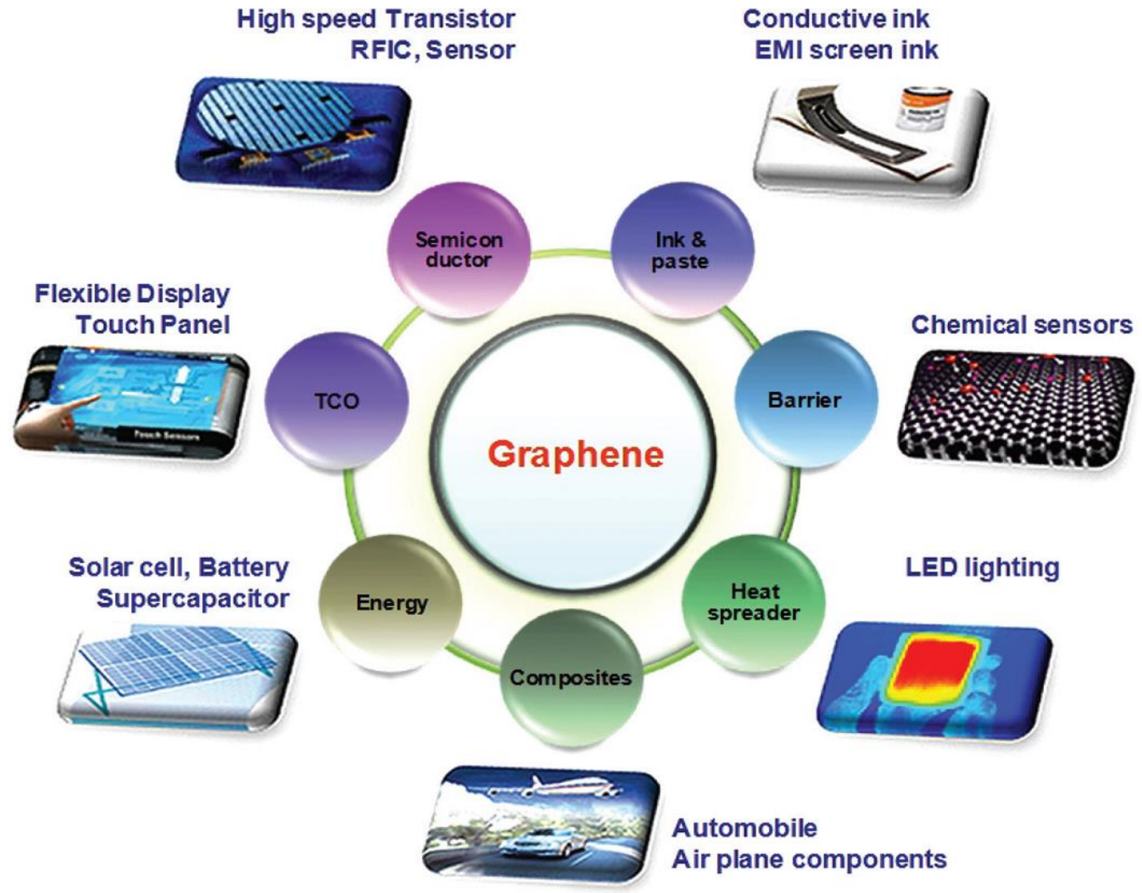


Fig. 3 Overview of Applications of Graphene in different sectors ranging from conductive ink to chemical sensors, light emitting devices, composites, energy, touch panels and high frequency electronics.

Ferrari et al., *Nanoscale* 2015;7:4598

Aplicações de grafeno e materiais relacionados

Tratamento de água:

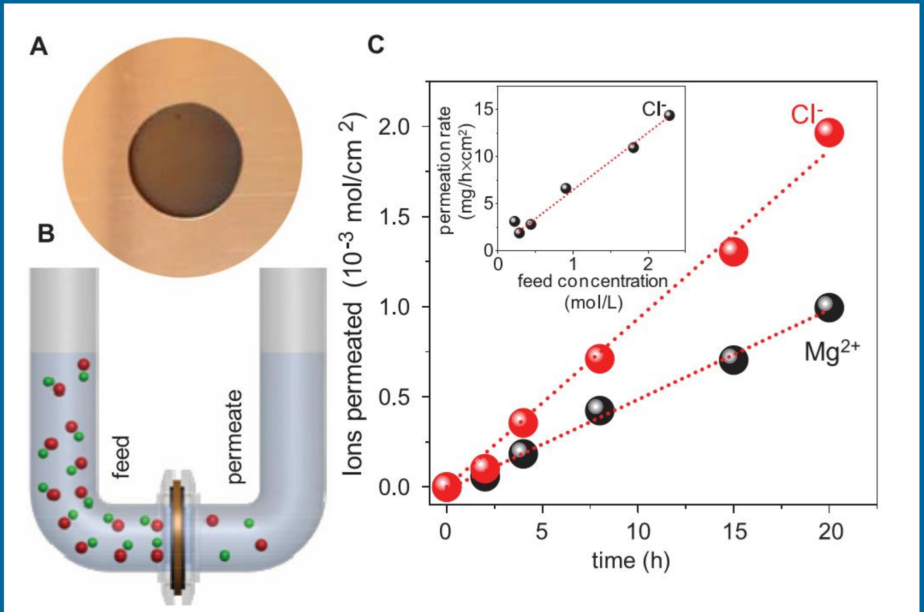


Fig. 1. Ion permeation through GO laminates. (**A**) Photograph of a GO membrane covering a 1-cm opening in a copper foil. (**B**) Schematic of the experimental setup. A U-shaped tube 2.5 cm in diameter is divided by the GO membrane into two compartments referred to as feed and permeate. Each is filled to a typical level of ~20 cm. Magnetic stirring is used so as to ensure no concentration gradients. (**C**) Permeation through a 5-μm-thick GO membrane from the feed compartment with a 0.2 M solution of $MgCl_2$. (Inset) Permeation rates as a function of *C* in the feed solution. Within our experimental accuracy (variations by a factor of <40% for membranes prepared from different GO suspensions), chloride rates were found the same for $MgCl_2$, KCl, and $CuCl_2$. Dotted lines are linear fits.

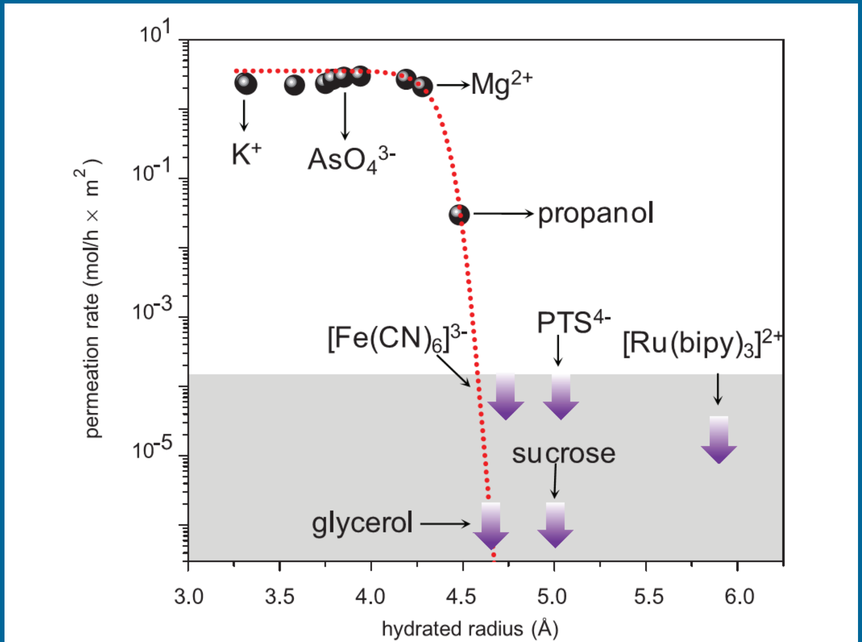


Fig. 2. Sieving through the atomic-scale mesh. The shown permeation rates are normalized per 1 M feed solution and measured by using 5-μm-thick membranes. Some of the tested chemicals are named here; the others can be found in table S1 (*25*). No permeation could be detected for the solutes shown within the gray area during measurements lasting for at least 10 days. The thick arrows indicate our detection limit, which depends on a solute. Several other large molecules—including benzoic acid, DMSO, and toluene—were also tested and exhibited no detectable permeation. The dashed curve is a guide to the eye, showing an exponentially sharp cutoff at 4.5 Å, with a width of ≈0.1 Å.

Joshi et al., *Science* 2014;343:752

Aplicações de grafeno e materiais relacionados

Tratamento de água:

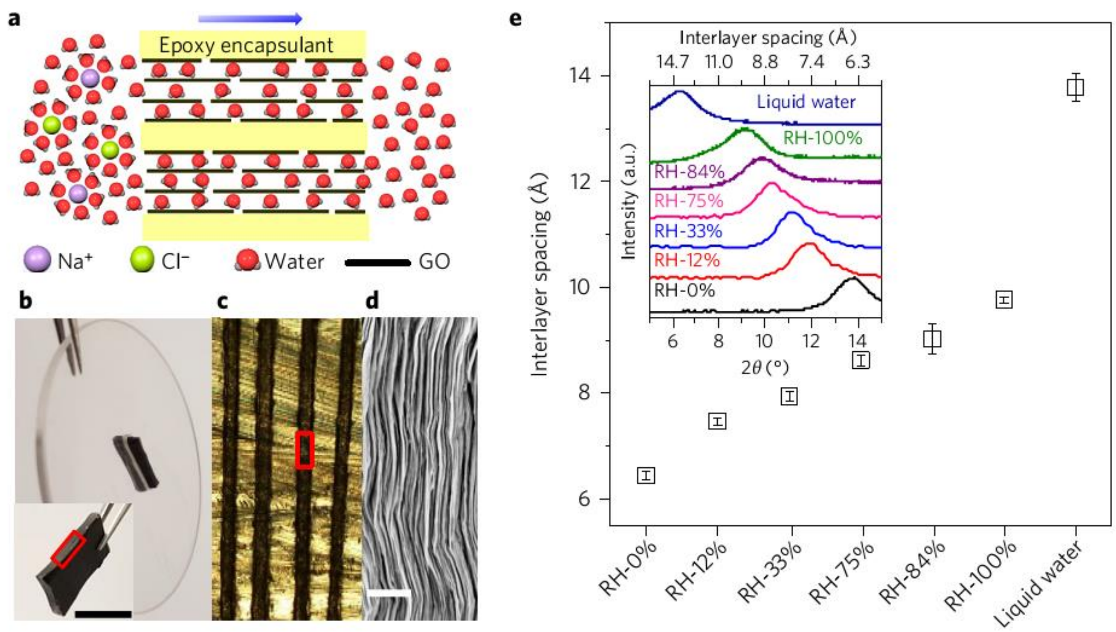


Figure 1 | Physically confined GO membranes with tunable interlayer spacing. a, Schematic illustrating the direction of ion/water permeation along graphene planes. **b**, Photograph of a PCGO membrane glued into a rectangular slot within a plastic disk of 5 cm in diameter. Inset: photo of the PCGO stack before it was placed inside the slot. Scale bar, 5 mm. **c**, Optical micrograph of the cross-sectional area marked by a red rectangle in **b**, which shows 100-µm-thick GO laminates (black) embedded in epoxy. Epoxy is seen in light yellow with dark streaks because of surface scratches. **d**, Scanning electron microscopy image from the marked region in **c**. Scale bar, 1 µm. **e**, Humidity-dependent interlayer spacing, *d*, found using X-ray diffraction (inset). The case of liquid water is also shown. Error bars denote standard deviations using at least two measurements from three different samples.

Abraham et al., *Nature Nanotechonology* 2017;12:546-550

Aplicações de grafeno e materiais relacionados

Tratamento de água:

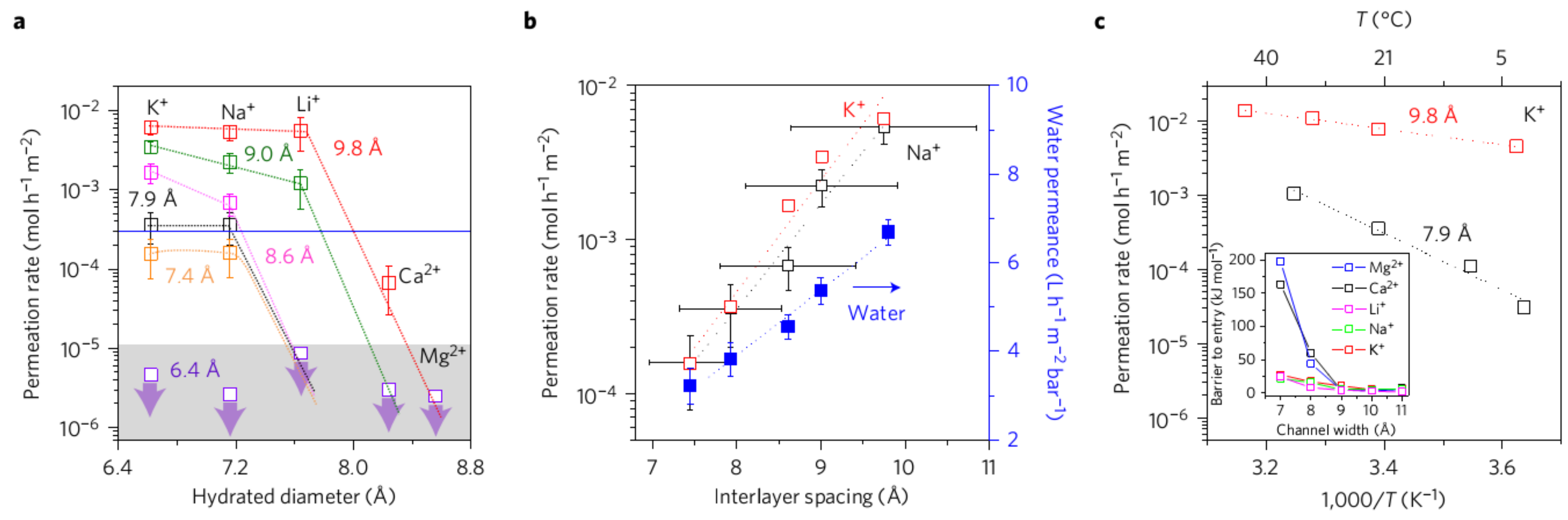


Figure 2 | Tunable ion sieving. a, Permeation rates through PCGO membranes with different interlayer distances (colour coded). The salts used were KCl, NaCl, LiCl, $CaCl_2$ and $MgCl_2$. The hydrated diameters are taken from ref. 6 (Supplementary Section 4). Dashed lines are guides to the eye indicating a rapid cutoff in salt permeation, which is dependent on the interlayer spacing, *d*. Grey area shows the below-detection limit for our measurements lasting five days, with arrows indicating the limits for individual salts. The horizontal blue line indicates our detection limit for Cl^-. Above the latter limit, we found that both cations and anions permeated in stoichiometric quantities. Error bars denote standard deviation. **b**, Permeation rates for K^+ and Na^+ depend exponentially on the interlayer distance (left axis). Water permeation varied only linearly with *d* (blue squares, right axis). The dotted lines are best fits. The horizontal error bars correspond to a half-width for the diffractions peaks in Fig. 1e and are same for all the three data sets. The vertical error bars indicate the standard deviation. The errors for K^+ are similar to those for Na^+ and have been omitted for clarity. **c**, Temperature dependence for K^+ permeation. Dotted lines are best fits to the Arrhenius behaviour. Inset: energy barriers for various ions and different *d*, as found in our molecular dynamics simulations.

Abraham et al., *Nature Nanotechonology* 2017;12:546-550

Aplicações de grafeno e materiais relacionados

Tratamento de água:

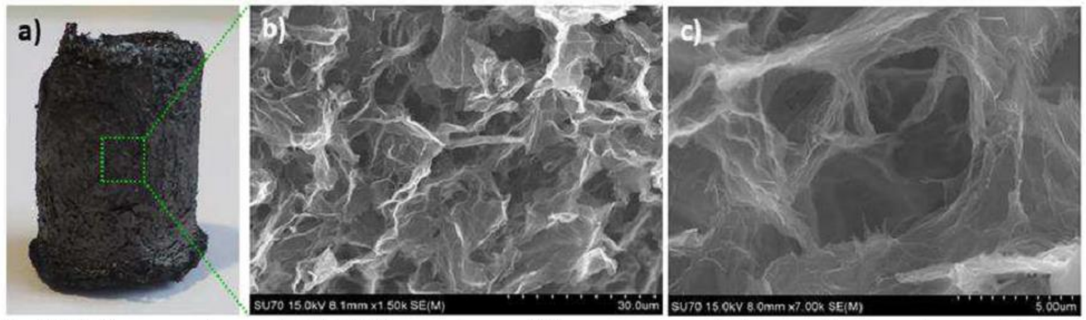


Fig. 1. GO foam a) and SEM images of its porous internal structure b) and c).

Gonçalves et al., *Graphene Week 2015*

“Parecido com pacotinhos de chá, um novo produto desenvolvido por uma equipa de investigadores da Universidade de Aveiro (UA), que contém óxido de grafeno, é capaz de descontaminar água com metais tóxicos como o mercúrio.
Os estudos demonstraram que, com apenas dez miligramas de óxido de grafeno por cada litro de água, contaminado com 50 microgramas de mercúrio, foi possível remover, ao fim de 24 horas, cerca de 95% desse metal perigoso para o sistema nervoso central.”

http://www.publico.pt/ciencia/noticia/cha-de-grafeno-extrai-metais-pesados-da-agua-1702039

Aplicações de grafeno e materiais relacionados

Detecção de compostos por adsorção:

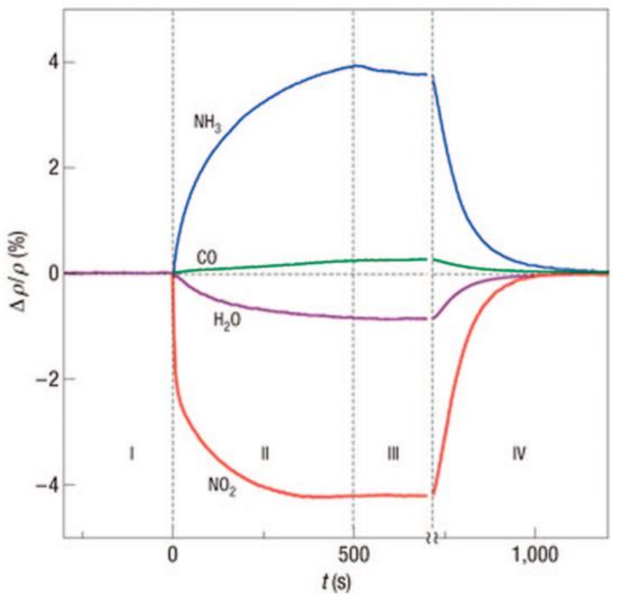


Figure 11. The lack of surface states in graphene makes possible the detection of even single adsorbate. The direction of change in the figure indicates the sign of induced carriers (holes for H_2O and NO_2; electrons for CO and NH_3). [Reprinted with permission from *Nature* (http://www.nature.com), ref 21. Copyright 2007 Nature Publishing Group.]

Allen et al., *Chem. Rev.* 2010;110:132

Aplicações do grafeno

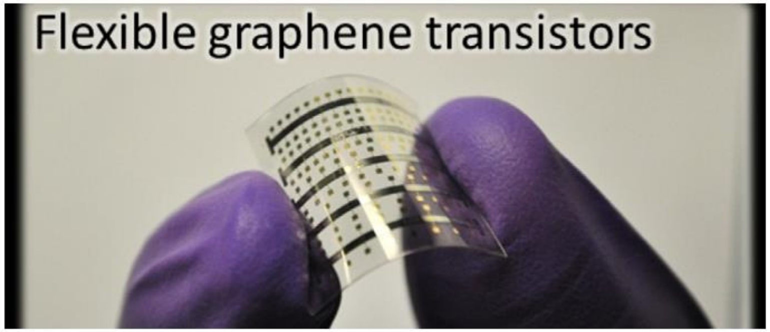


FIGURE 5

Ultra-thin flexible graphene transistor. Image reproduced from Ref. [58] with permission from IOPScience.

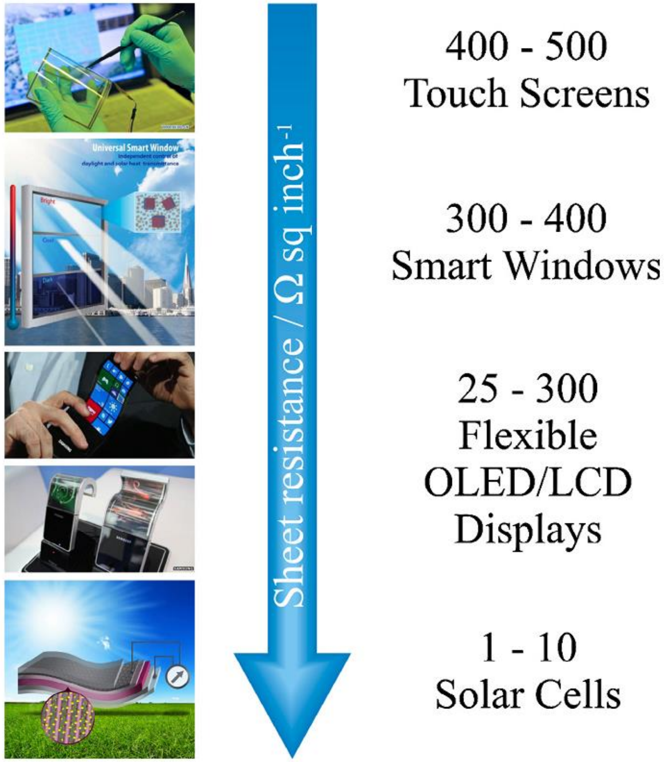


FIGURE 4

Potential applications graphene has to offer, depending upon the resistivity of the type of graphene. Adapted from Ref. [53] with permission from IOPScience.

Randviir et al., *Mater. Today* 2014;17:426

Aplicações do grafeno

Fig. 7 NOKIA Morph:[1] the future mobile device will act as a gateway. It will connect users to local environment, as well as the global internet. It is an attentive device that shapes according to the context. It can change its form from rigid to flexible and stretchable.[1]

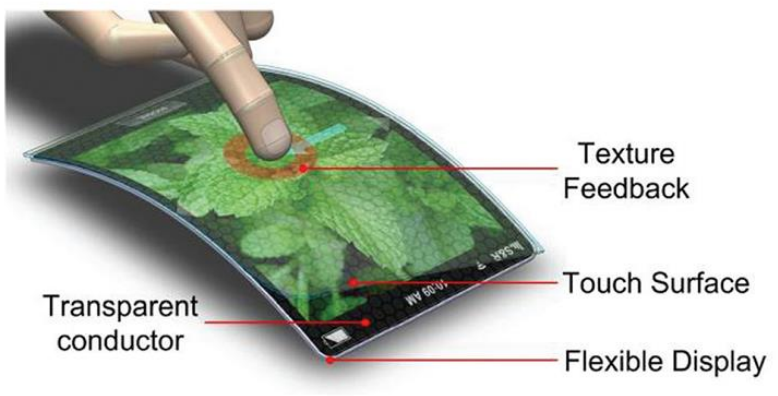
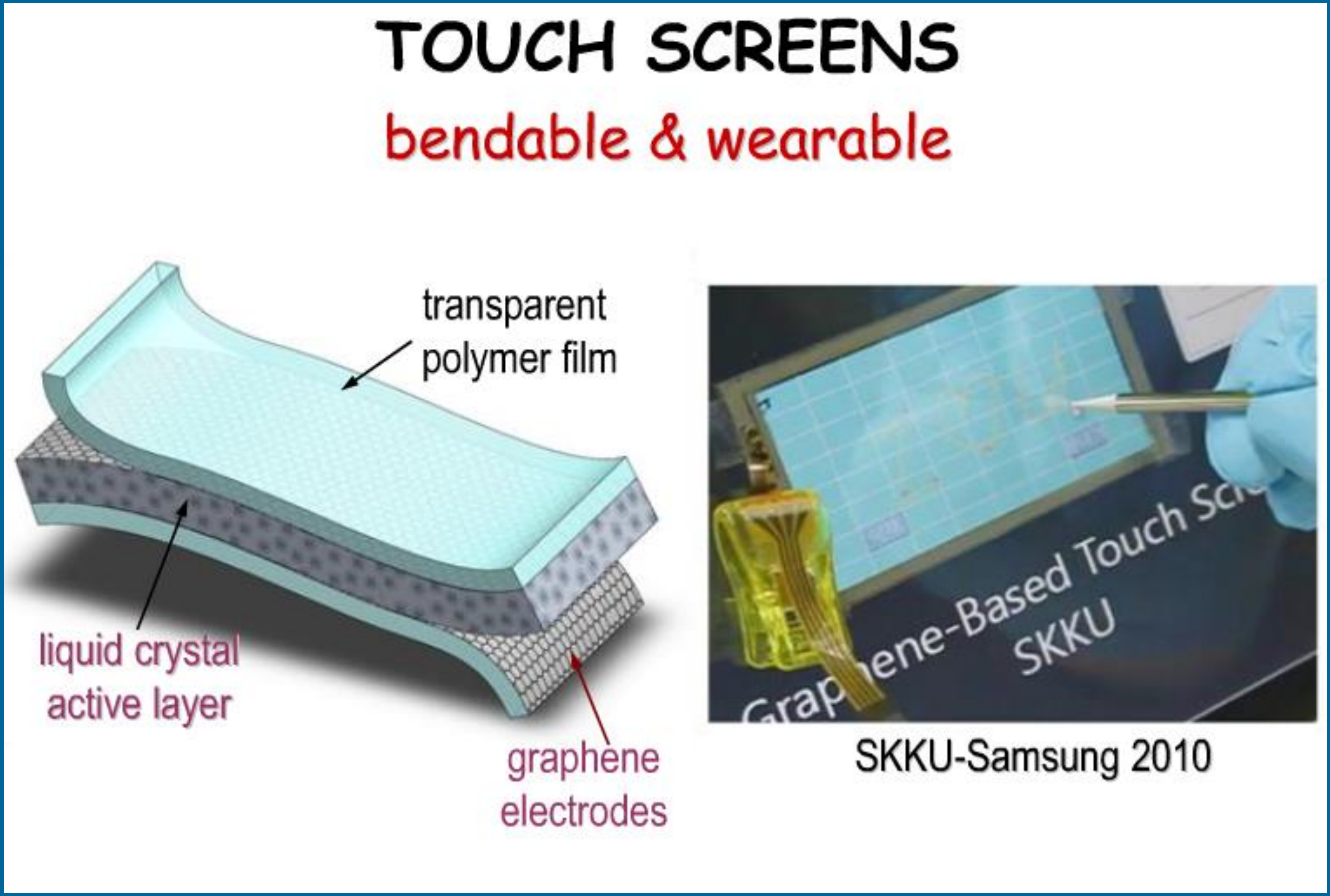


Fig. 95 Graphene-based electrotactile display. Adapted from ref. 1758.

Ferrari et al., *Nanoscale* 2015;7:4598

Aplicações do grafeno



http://www.materialstoday.com/view/8249/the-carbon-new-age/

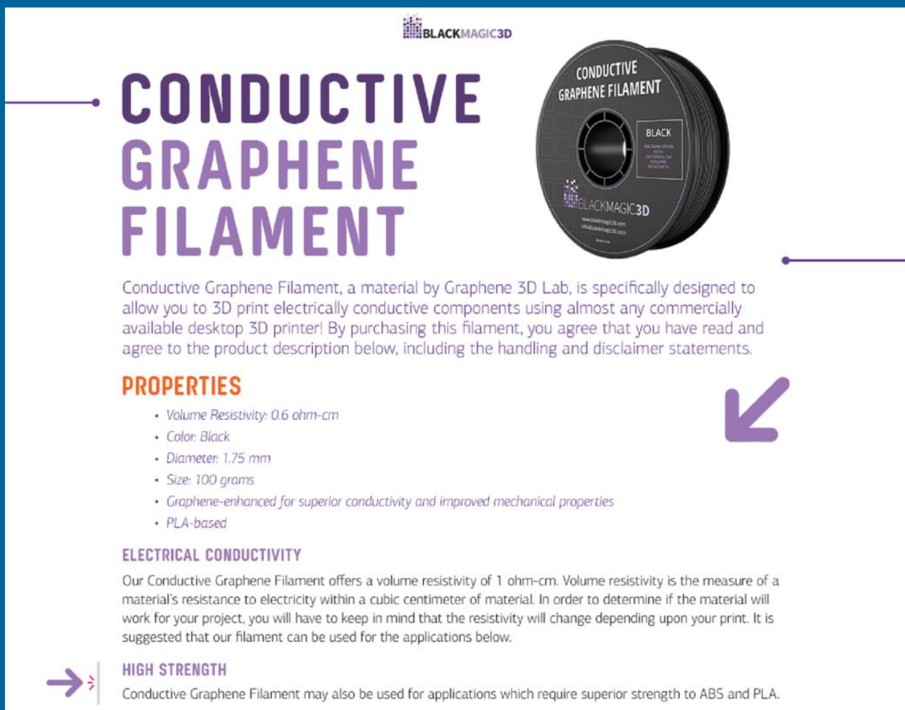
Aplicações do grafeno

Impressão 3D:

http://www.graphene3dlab.com/

Aplicações do grafeno

Impressão 3D:



BLACKMAGIC3D

CONDUCTIVE GRAPHENE FILAMENT

Conductive Graphene Filament, a material by Graphene 3D Lab, is specifically designed to allow you to 3D print electrically conductive components using almost any commercially available desktop 3D printer! By purchasing this filament, you agree that you have read and agree to the product description below, including the handling and disclaimer statements.

PROPERTIES

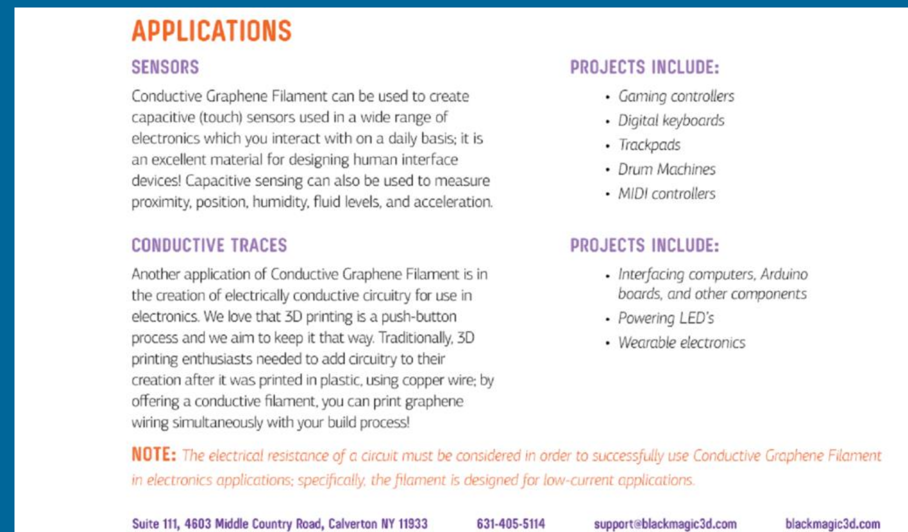
- *Volume Resistivity: 0.6 ohm-cm*
- *Color: Black*
- *Diameter: 1.75 mm*
- *Size: 100 grams*
- *Graphene-enhanced for superior conductivity and improved mechanical properties*
- *PLA-based*

ELECTRICAL CONDUCTIVITY

Our Conductive Graphene Filament offers a volume resistivity of 1 ohm-cm. Volume resistivity is the measure of a material's resistance to electricity within a cubic centimeter of material. In order to determine if the material will work for your project, you will have to keep in mind that the resistivity will change depending upon your print. It is suggested that our filament can be used for the applications below.

HIGH STRENGTH

Conductive Graphene Filament may also be used for applications which require superior strength to ABS and PLA.



APPLICATIONS

SENSORS

Conductive Graphene Filament can be used to create capacitive (touch) sensors used in a wide range of electronics which you interact with on a daily basis; it is an excellent material for designing human interface devices! Capacitive sensing can also be used to measure proximity, position, humidity, fluid levels, and acceleration.

PROJECTS INCLUDE:

- *Gaming controllers*
- *Digital keyboards*
- *Trackpads*
- *Drum Machines*
- *MIDI controllers*

CONDUCTIVE TRACES

Another application of Conductive Graphene Filament is in the creation of electrically conductive circuitry for use in electronics. We love that 3D printing is a push-button process and we aim to keep it that way. Traditionally, 3D printing enthusiasts needed to add circuitry to their creation after it was printed in plastic, using copper wire; by offering a conductive filament, you can print graphene wiring simultaneously with your build process!

PROJECTS INCLUDE:

- *Interfacing computers, Arduino boards, and other components*
- *Powering LED's*
- *Wearable electronics*

NOTE: *The electrical resistance of a circuit must be considered in order to successfully use Conductive Graphene Filament in electronics applications; specifically, the filament is designed for low-current applications.*

Suite 111, 4603 Middle Country Road, Calverton NY 11933 631-405-5114 support@blackmagic3d.com blackmagic3d.com

http://www.graphene3dlab.com/

Aplicações do grafeno

Impressão 3D:

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Aplicações do grafeno

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http://www.graphene3dlab.com/

Bibliografia recomendada

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  - “Random walk to graphene – story behind”,

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  - “Graphene: materials in the flatland”,

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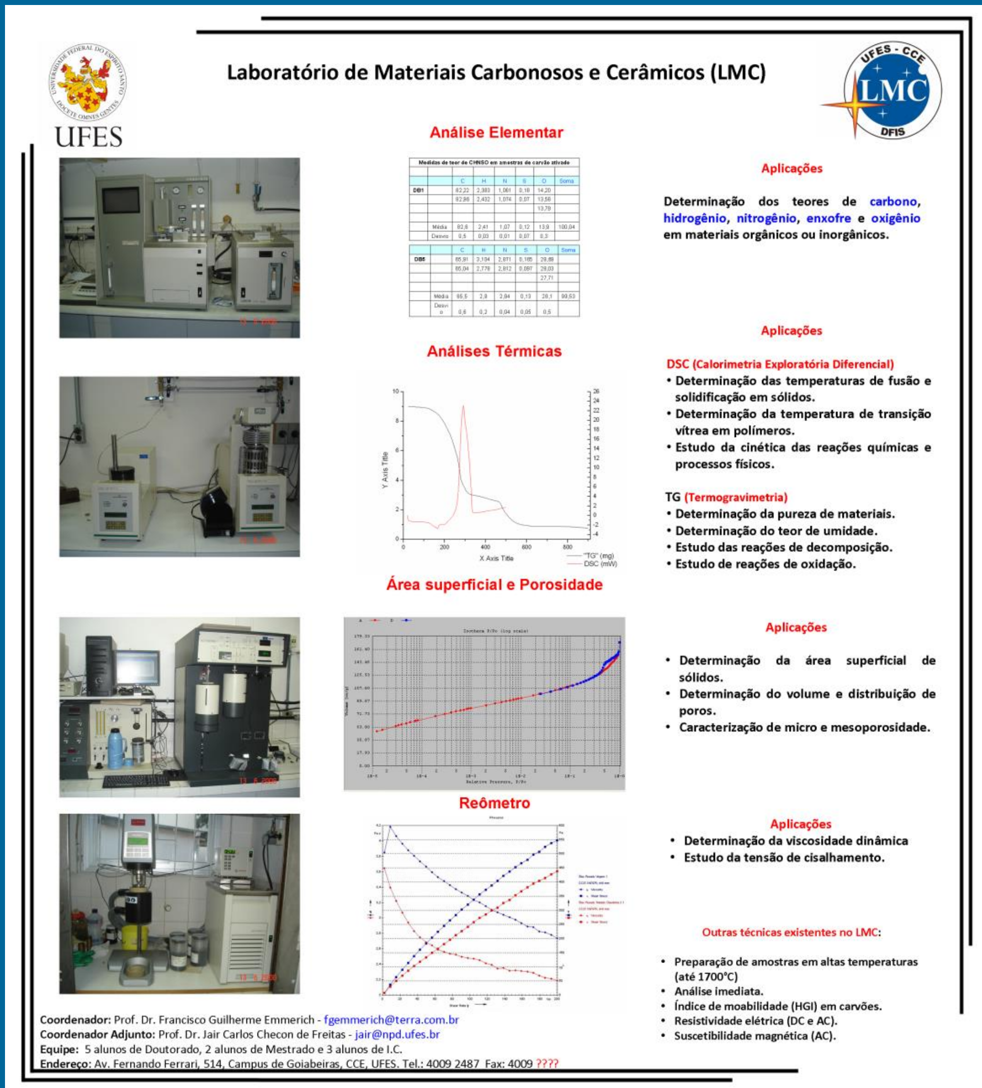
  - “O Prêmio Nobel de 2010: Grafeno: o início de uma nova era para o carbono”,

    http://video.if.usp.br/video/o-pr%C3%AAmio-nobel-de-2010-grafeno-o-in%C3%ADcio-de-uma-nova-era-para-o-carbono
- Conferência de Jonathan Coleman, Trinity College, Dublin (2012):
  - “Tiny but mighty: How today’s nanomaterials will lead to tomorrow’s technologies”,

    https://www.youtube.com/watch?v=HXYnvQliX6g

Contato: dúvidas, comentários, sugestões, etc.



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