IPM

IMAM KHOMEINI INTERNATIONAL UNIVERSITY

Graphene

& Dirac Fermion confinement

Zahra Khatibi

25 December 2011

Outline:

What is so special about Graphene?

- applications

What is Graphene?

- Structure
- Transport properties

Dirac fermions confinement

- Necessity

External magnetic field

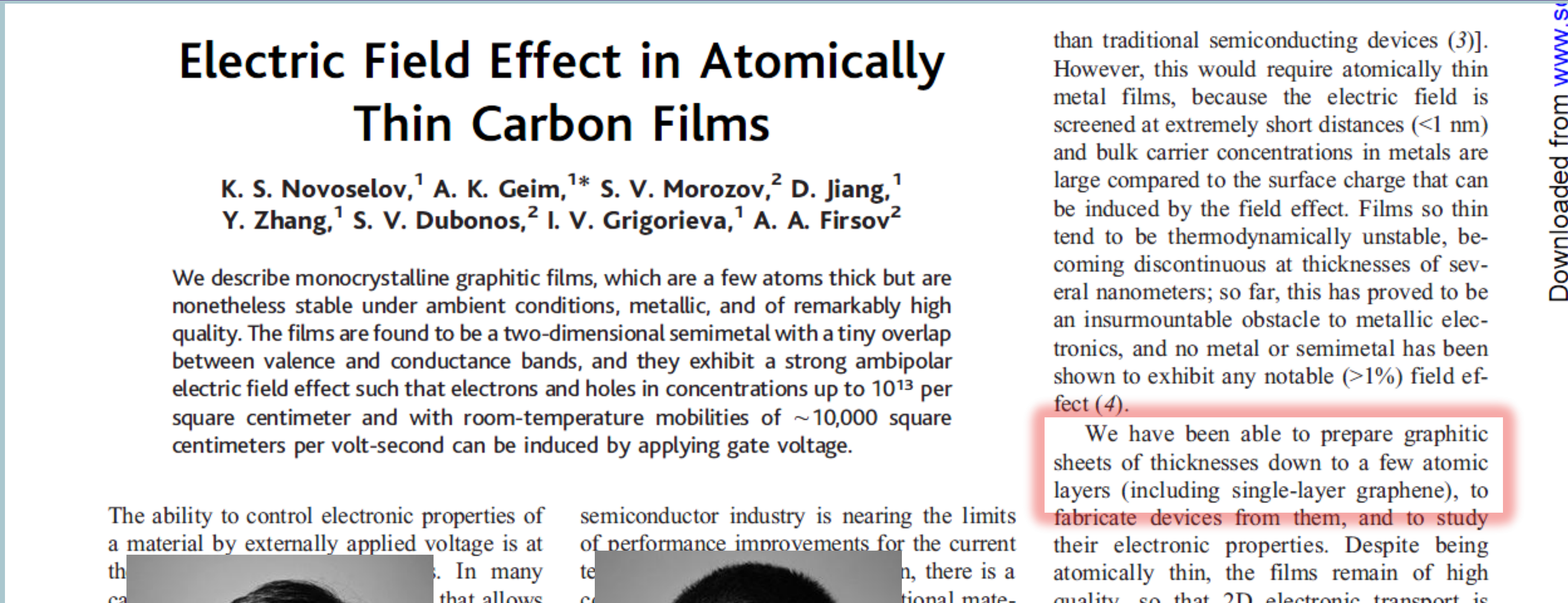
Strain engineering

- Pseudo magnetic fields

Conclusion

What is so special about Graphene?

What is so special about Graphene?



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.

The ability to control electronic properties of a material by externally applied voltage is at th . In many ca that allows

semiconductor industry is nearing the limits of performance improvements for the current te n, there is a c tional mate-

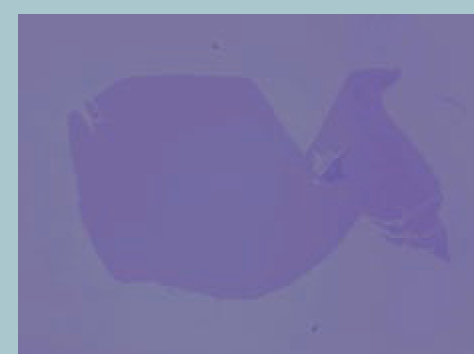
than traditional semiconducting devices (3)]. However, this would require atomically thin metal films, because the electric field is screened at extremely short distances (<1 nm) and bulk carrier concentrations in metals are large compared to the surface charge that can be induced by the field effect. Films so thin tend to be thermodynamically unstable, becoming discontinuous at thicknesses of several nanometers; so far, this has proved to be an insurmountable obstacle to metallic electronics, and no metal or semimetal has been shown to exhibit any notable (>1%) field effect (4).

We have been able to prepare graphitic sheets of thicknesses down to a few atomic layers (including single-layer graphene), to fabricate devices from them, and to study their electronic properties. Despite being atomically thin, the films remain of high quality, so that 2D electronic transport is

Downloaded from www.sc

Andre Geim

Konstantin Novoselov



K. S. Novoselov, et al., SCIENCE VOL 306 666 (2004)

Graphene

has the strongest material stiffness ever measured (1.0 TPa)

has high thermal conductivity

is chemically stable

can withstand large current densities

has very high mobility

has ballistic transport over sub-micron scales

N.M.R Peres et al., J. Phys.: Condens. Matter 21 (2009) 344202

What is so special about Graphene?

IOP A website from the Institute of Physics

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physicsworld.com

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Electrons heat up in graphene

Oct 6, 2011 7 comments

Graphene bubbles could make better lenses

Sep 19, 2011 5 comments

Quantum-Hall confirmation helps define kilogram

Sep 16, 2011 15 comments

Graphene tunes in to terahertz radiation

Sep 12, 2011 1 comment

Graphene could make 'perfect' solar cells

Sep 5, 2011 11 comments

Flowing electrons magnetize graphene

Apr 14, 2011

Nanotech industry comes under fire

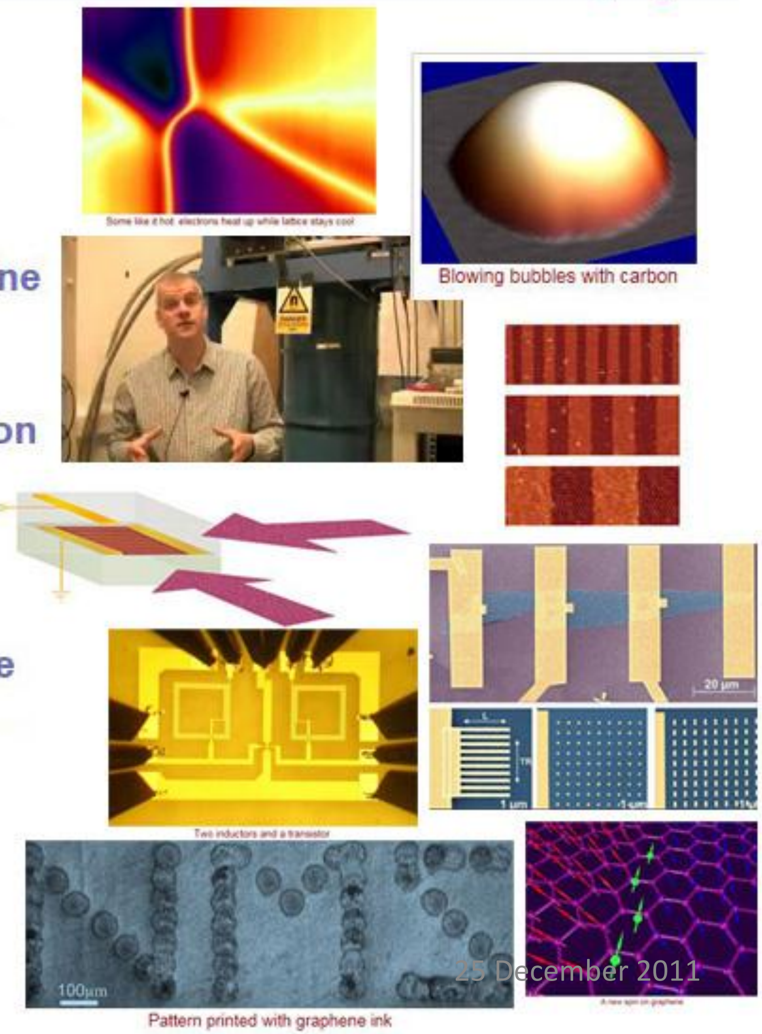
May 6, 2011 6 comments

Graphene integrated circuit is a first

Jun 9, 2011 2 comments

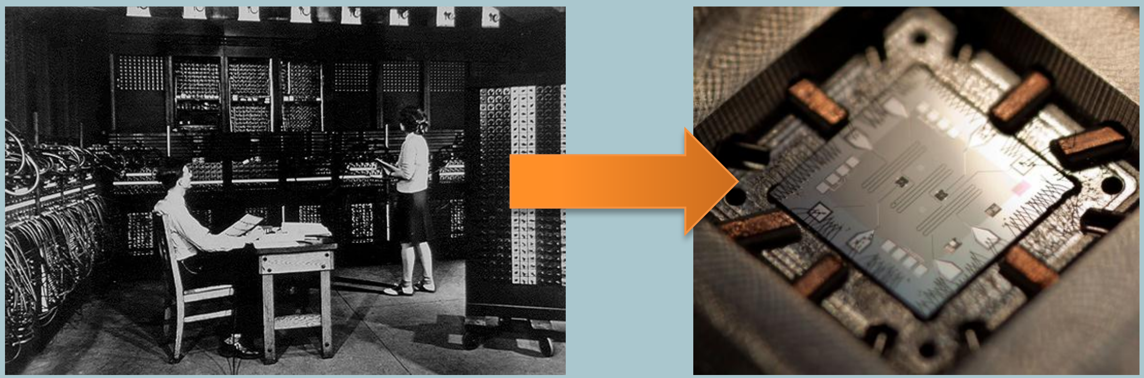
New ink prints graphene electronics

Dec 9, 2011 3 comments



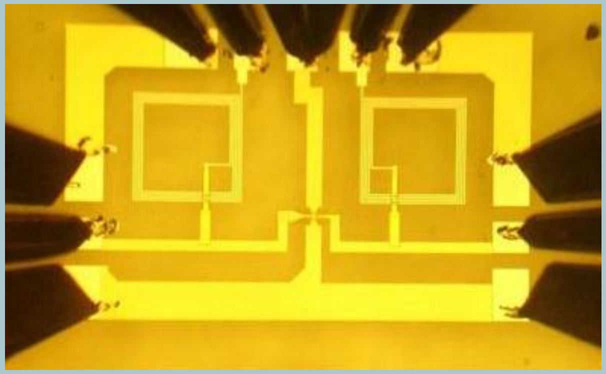
High performance transistors

silicon-based electronics



Quantum Von Neumann architecture in single chip

graphene-based electronics

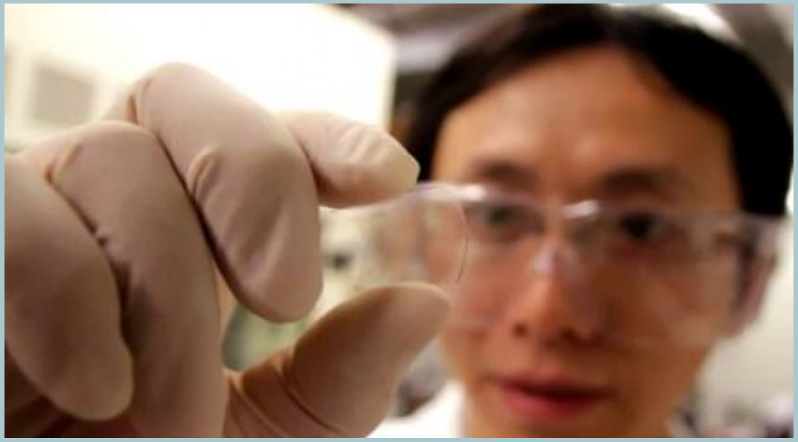


Two inductors and a transistor
Can be used as amplifiers and wireless communication

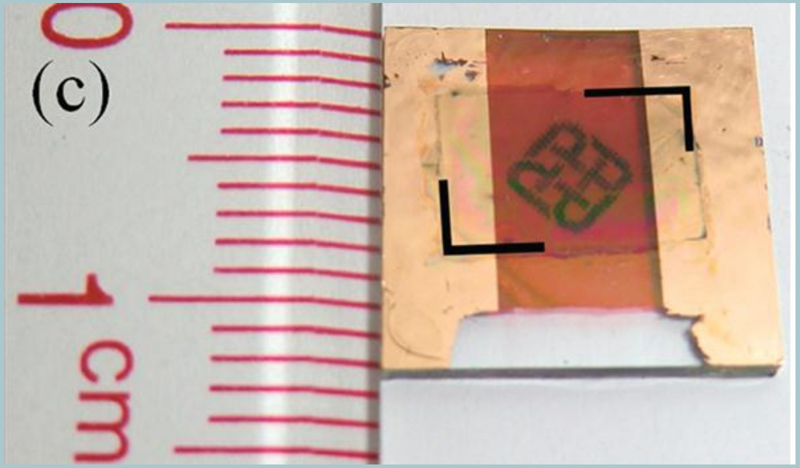
Perfect solar cells

Out of 1000 watts of sunlight

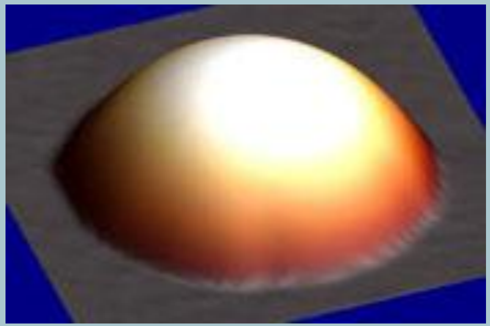
silicon solar cell: 14 watts
graphene-based solar cell: 1.3 watts



graphene-based hybrid film on a flexible plastic substrate

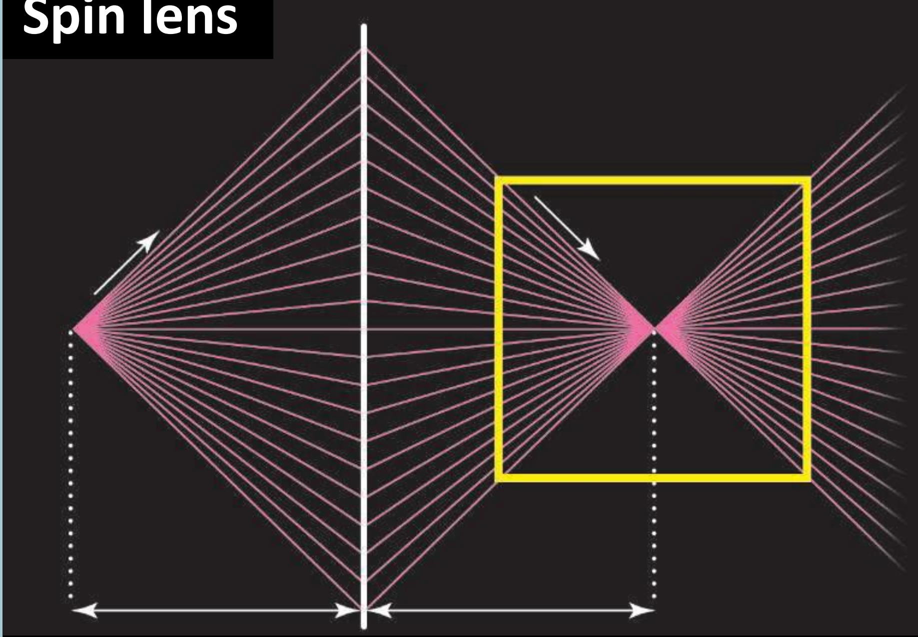


Better lenses

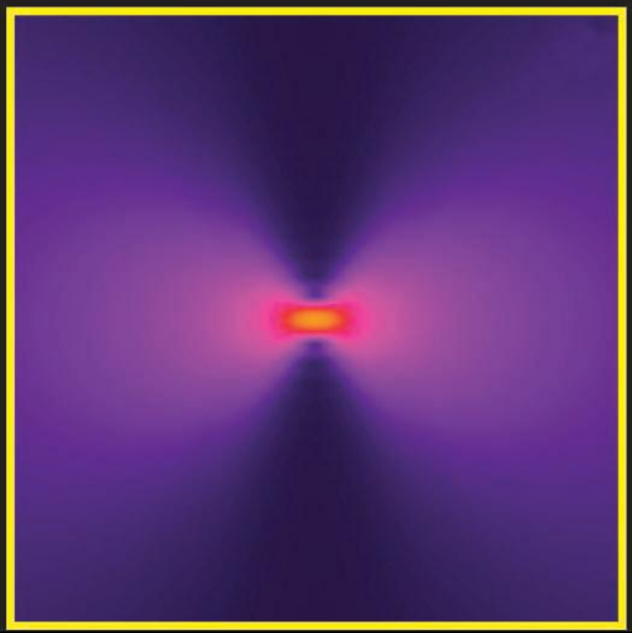


mobile-phone cameras, webcams and auto-focusing eye glasses

Spin lens



Veselago's lens



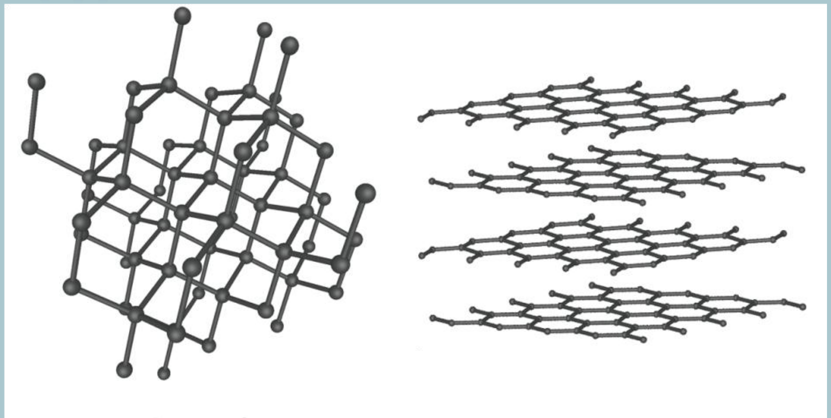
Computer simulation of electron charge density

www.physicsworld.com
SCIENCE VOL 315 1252 (2007)

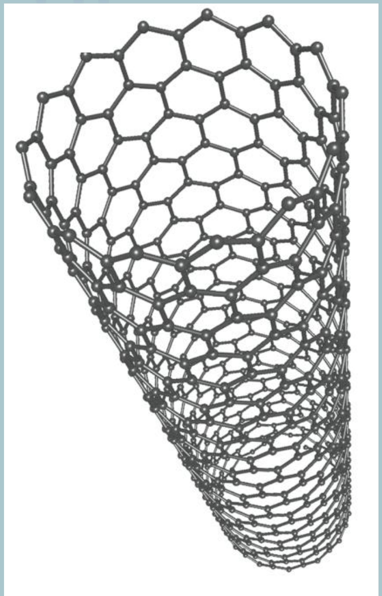
What is graphene?

Graphitic materials

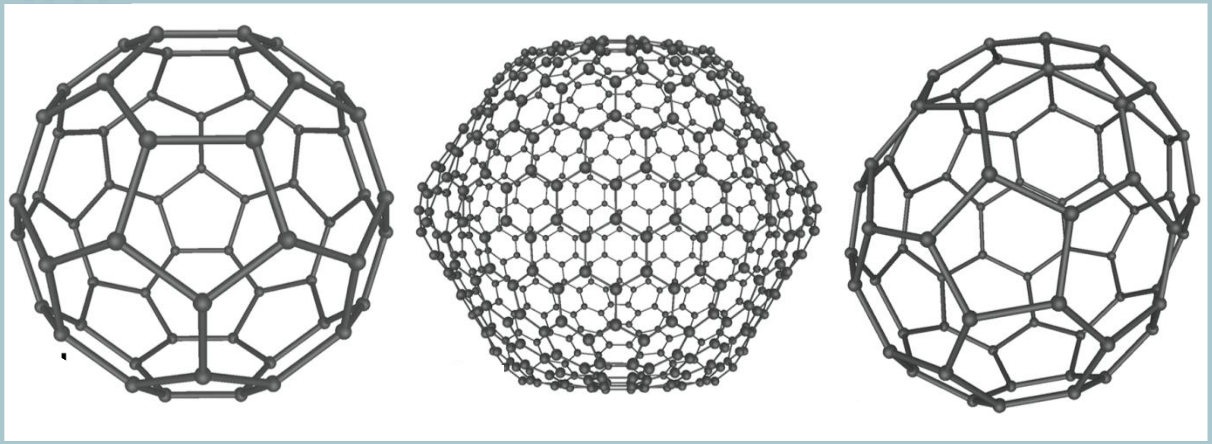
3 D



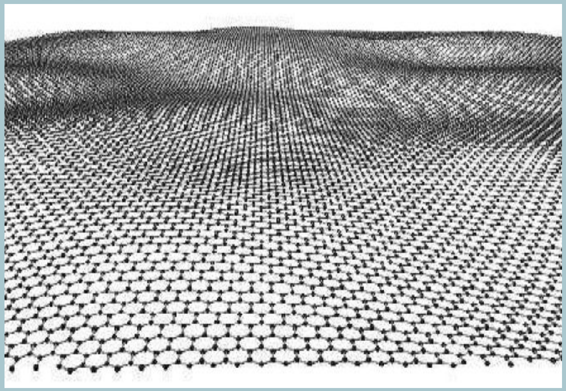
1 D



0 D

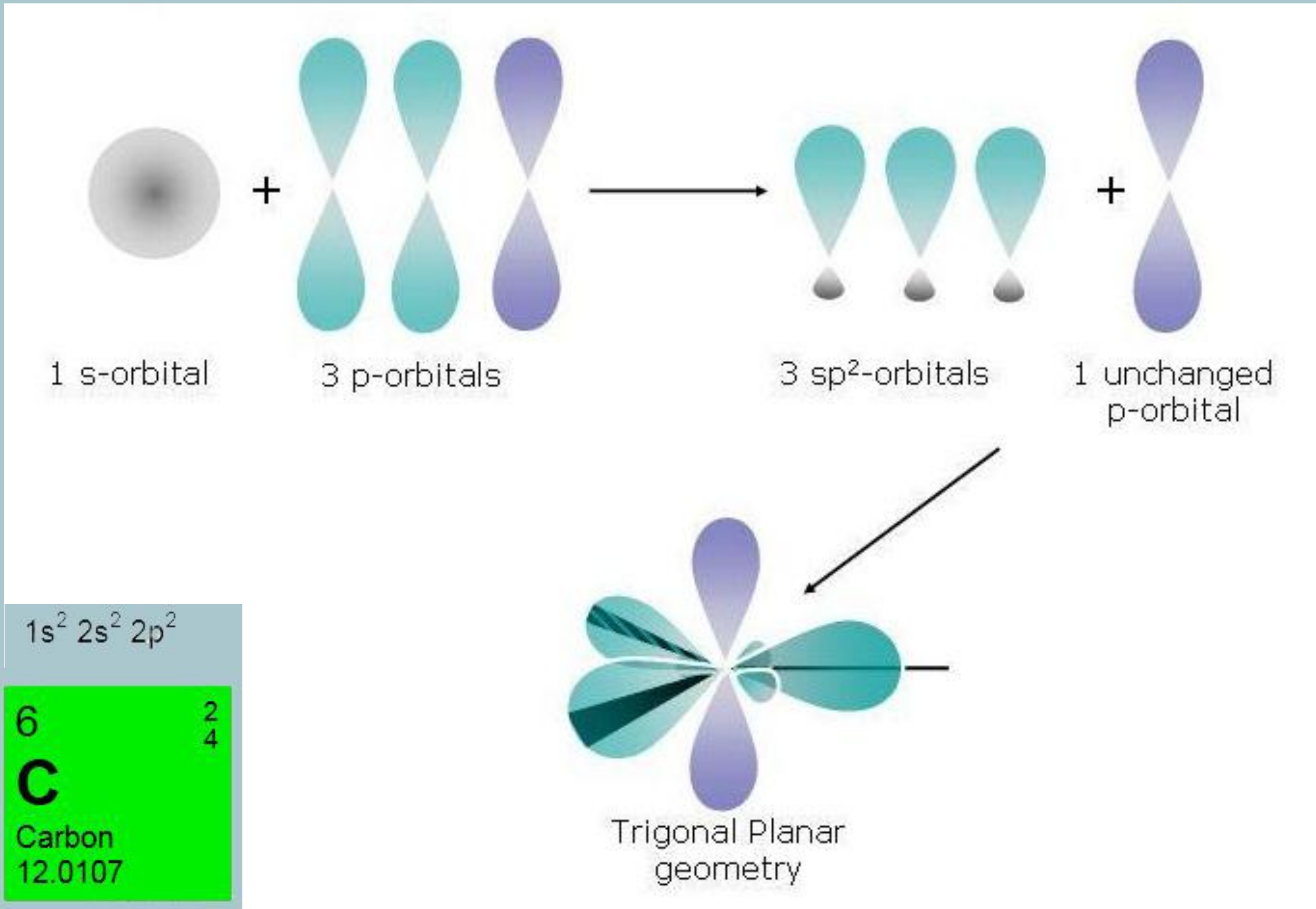


2 D

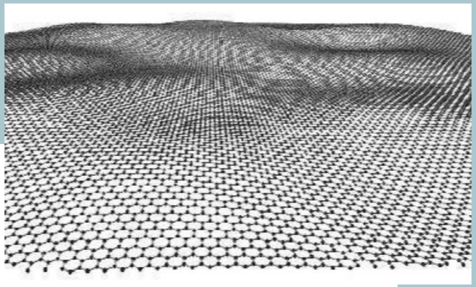


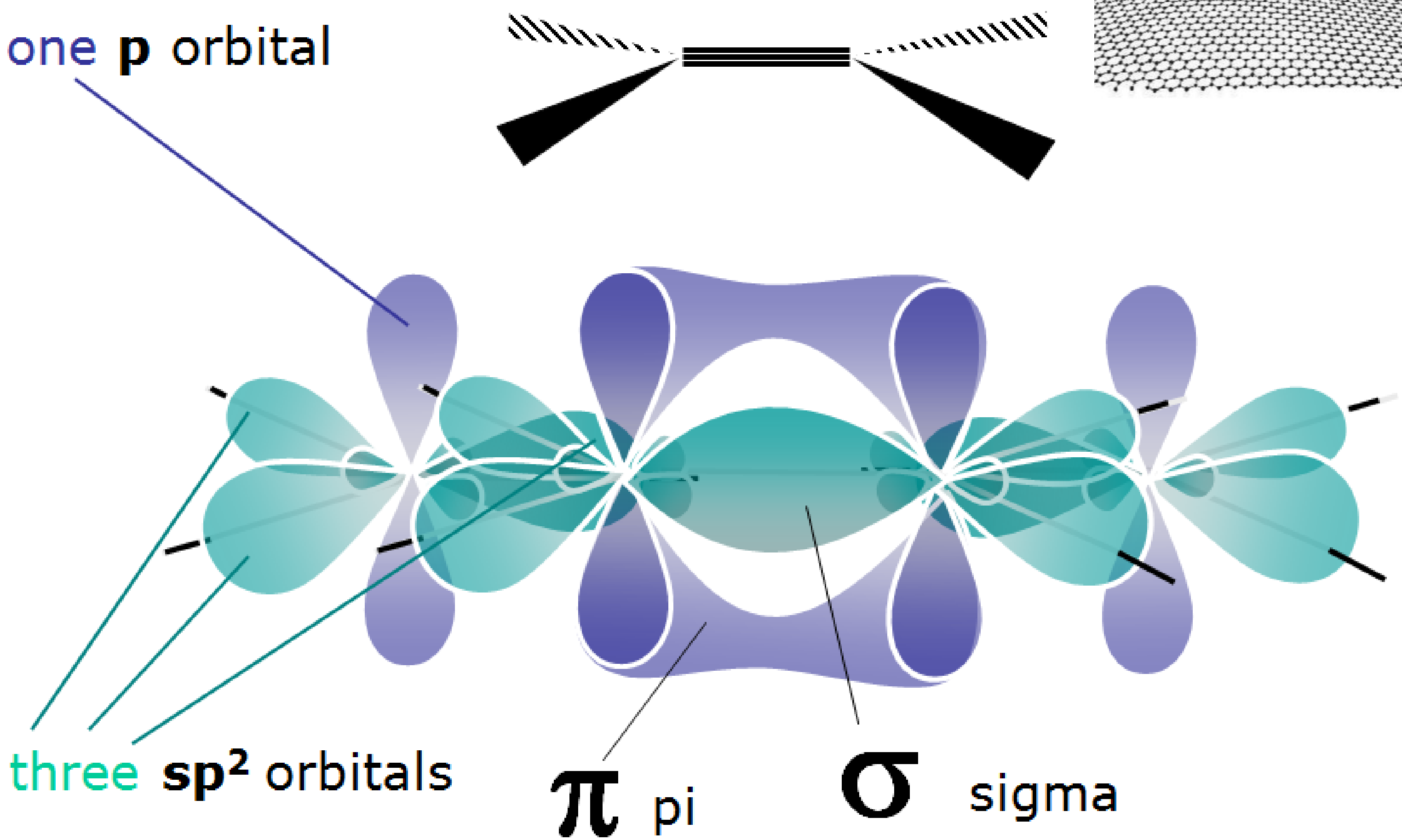
http://en.wikipedia.org

What is graphene? (structure)

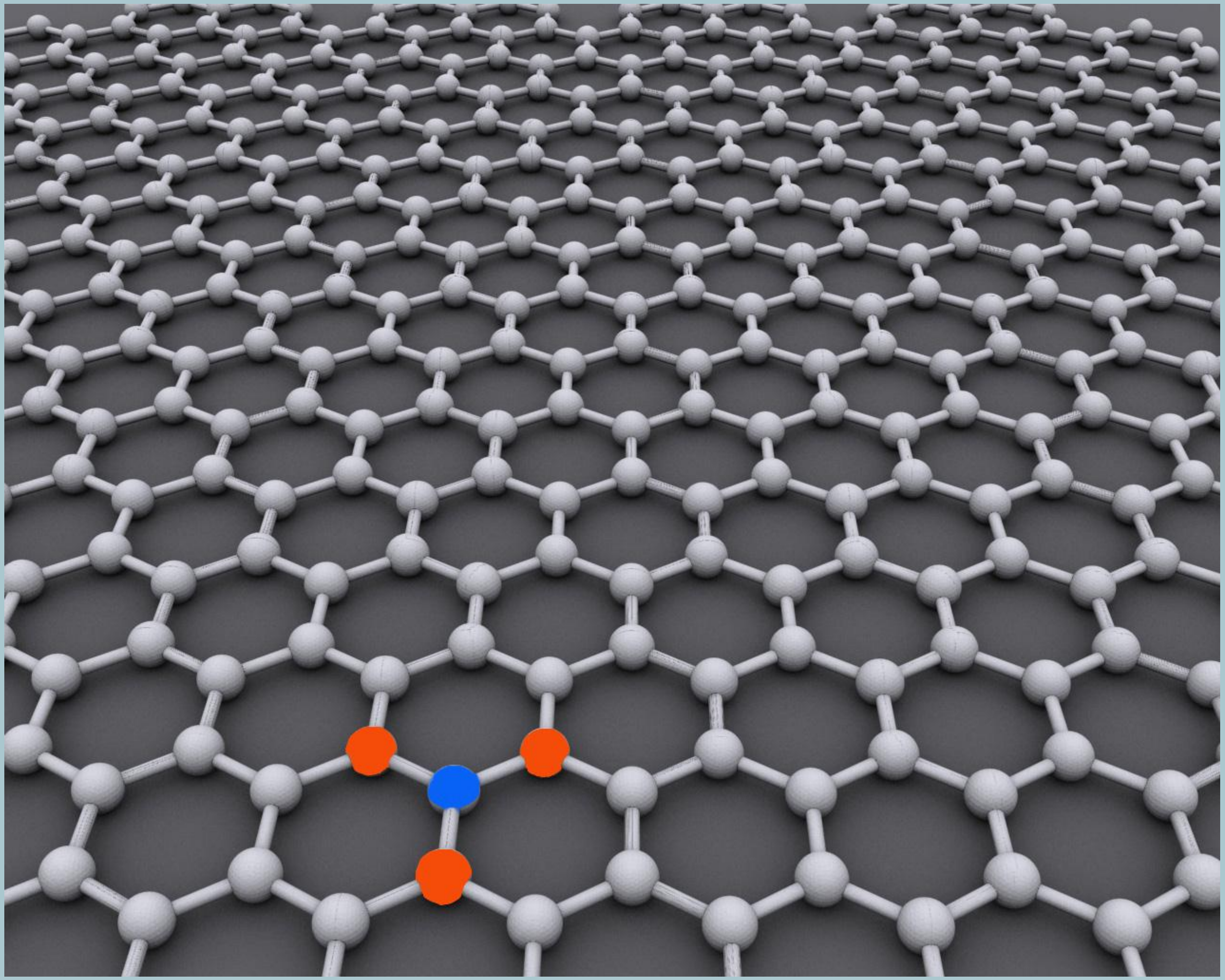


What is graphene? (structure)

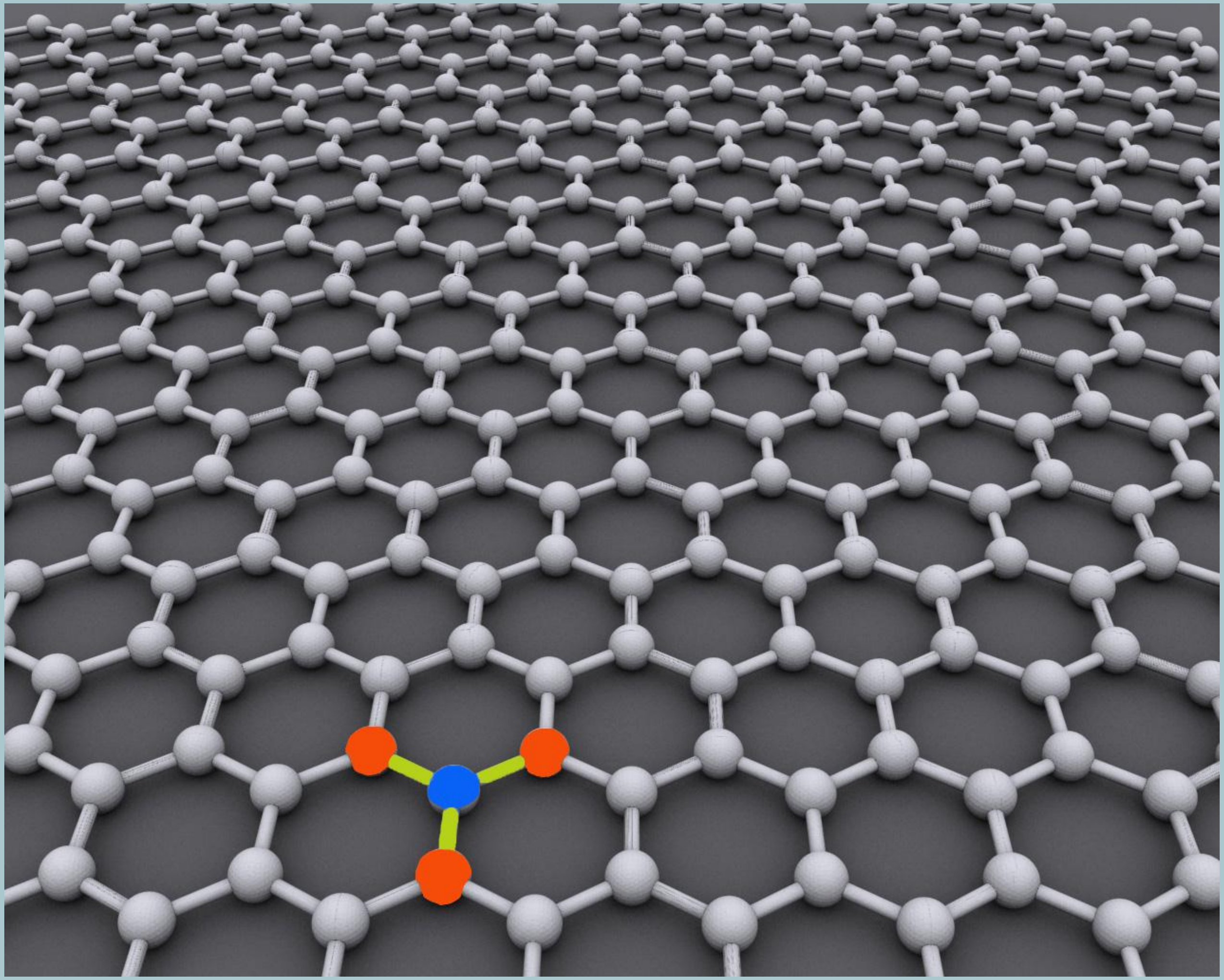




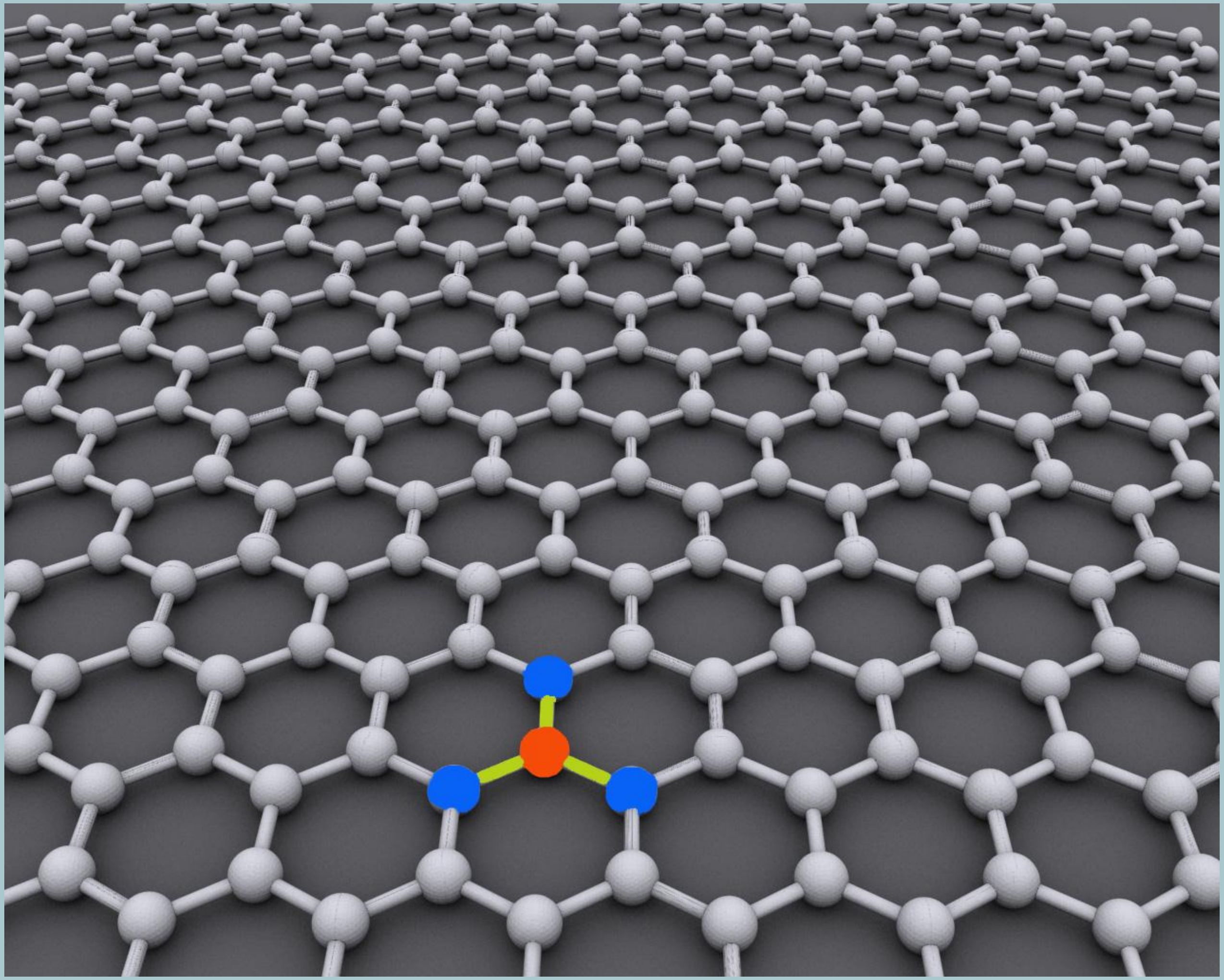
A honey comb lattice



A honey comb lattice



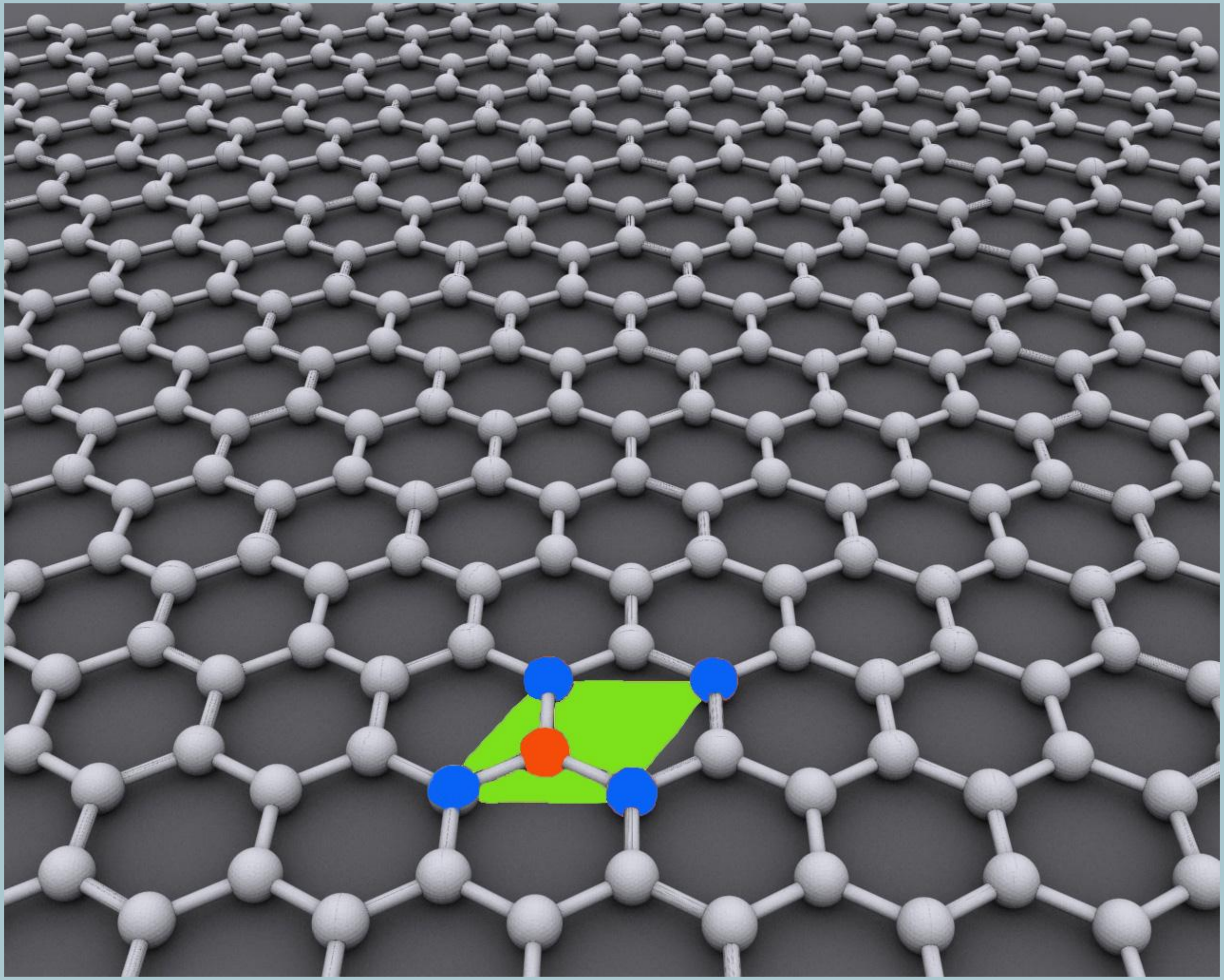
A honey comb lattice



A honey comb lattice

Sub lattices:

- A
- B

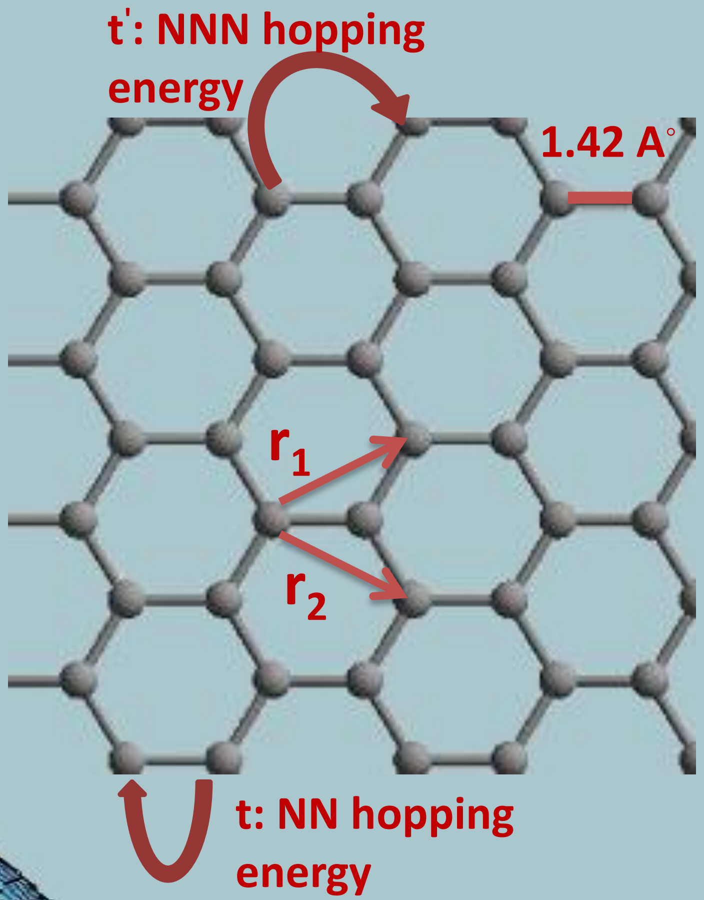


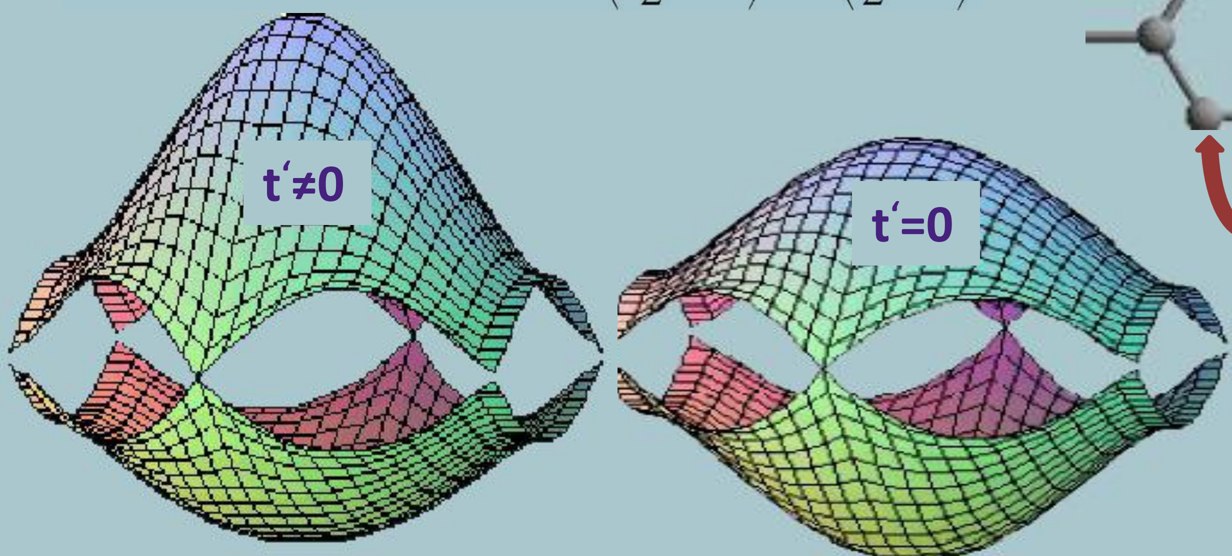
Band structure

$$H = -t \sum_{\langle i,j\rangle,\sigma} (a^{\dagger}_{\sigma,i} b_{\sigma,j} + \mathrm{H.c.}) - t' \sum_{\langle\langle i,j\rangle\rangle,\sigma} (a^{\dagger}_{\sigma,i} a_{\sigma,j} + b^{\dagger}_{\sigma,i} b_{\sigma,j} + \mathrm{H.c.})$$

$$E_{\pm}(\mathbf{k}) = \pm t\sqrt{3 + f(\mathbf{k})} - t' f(\mathbf{k})$$

$$f(\mathbf{k}) = 2\cos(\sqrt{3}k_y a) + 4\cos\left(\frac{\sqrt{3}}{2}k_y a\right)\cos\left(\frac{3}{2}k_x a\right)$$





G. Baskaran, S. A. Jafari, Novel Quantum Phenomena in Graphene

Dirac points

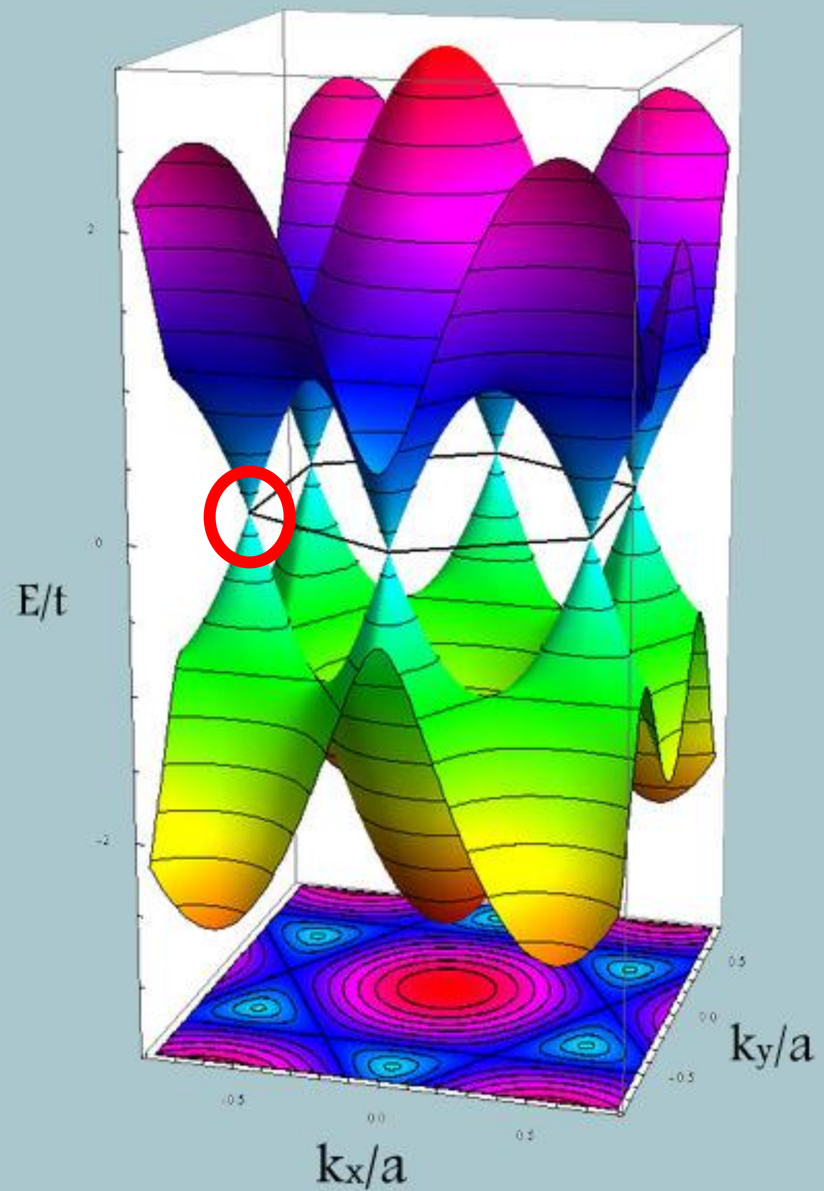
$$E(\mathbf{k}) = 0$$

Six Fermi points at six corners of BZ (only 2 are independent)

$$\boldsymbol{K} = \left(\frac{2\pi}{3a}, \frac{2\pi}{3\sqrt{3}a}\right), \quad \boldsymbol{K}' = \left(\frac{2\pi}{3a}, -\frac{2\pi}{3\sqrt{3}a}\right)$$

$$-iv_F\boldsymbol{\sigma}\cdot\nabla\psi(\mathbf{r}) = E\psi(\mathbf{r})$$

$$v_F \simeq 1\times10^6\ \mathrm{m/s}$$



http://en.wikipedia.org

Klein tunneling

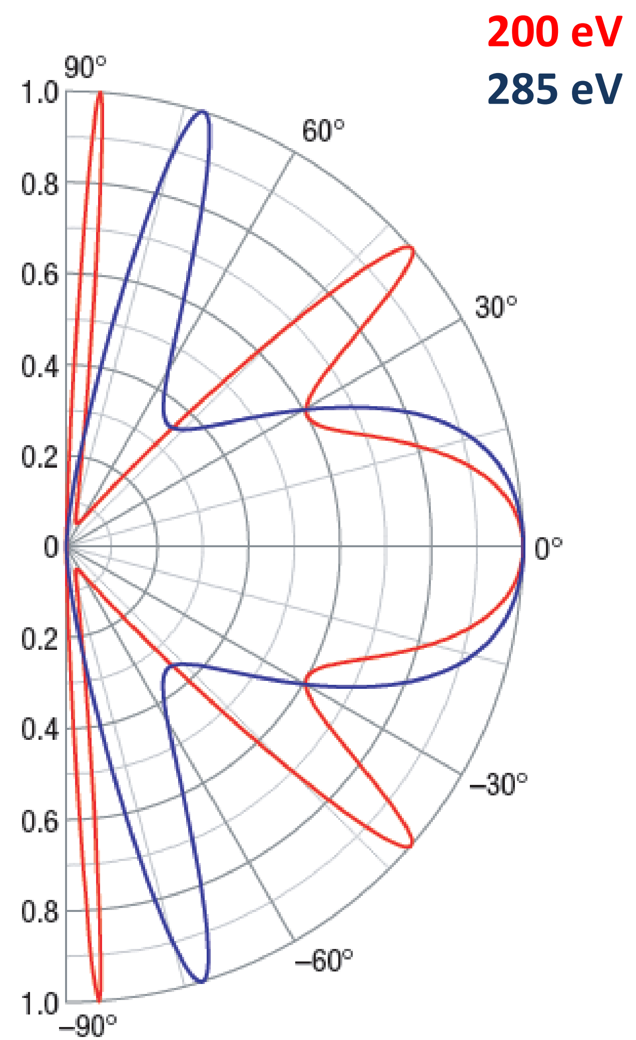
$$T = \frac{\cos^2\phi}{1 - \cos^2(q_x D)\sin^2\phi}$$

Transparent barriers for some angles

No backscattering

Lack of localization

for smooth potential
over atomic scale



Transmission probability

M.I.Katsnelson et al., nature physics VOL 2 620 (2006)

Dirac fermions confinement

Not the only but the most important reason

Graphene-based field effect transistors (FET)

high mobility & **ballistic transport**

at submicron distances

structures smaller than 10 nm with higher mobility → graphene → gapless spectrum → Flow spreading switch off ?

External magnetic field

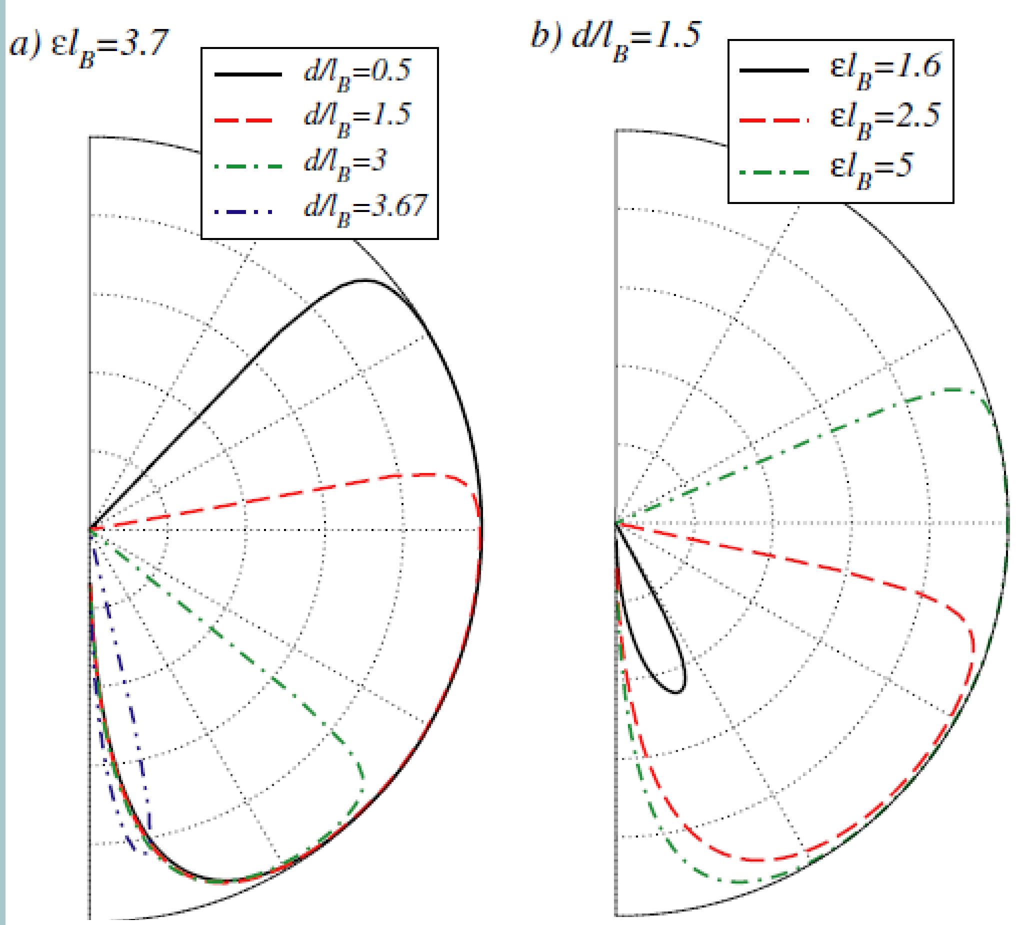
Inhomogeneous magnetic fields

$$B(x, y) = B_0 \theta(d^2 - x^2)$$

$$l_B \equiv \sqrt{c/eB_0},$$

no transmission is possible for

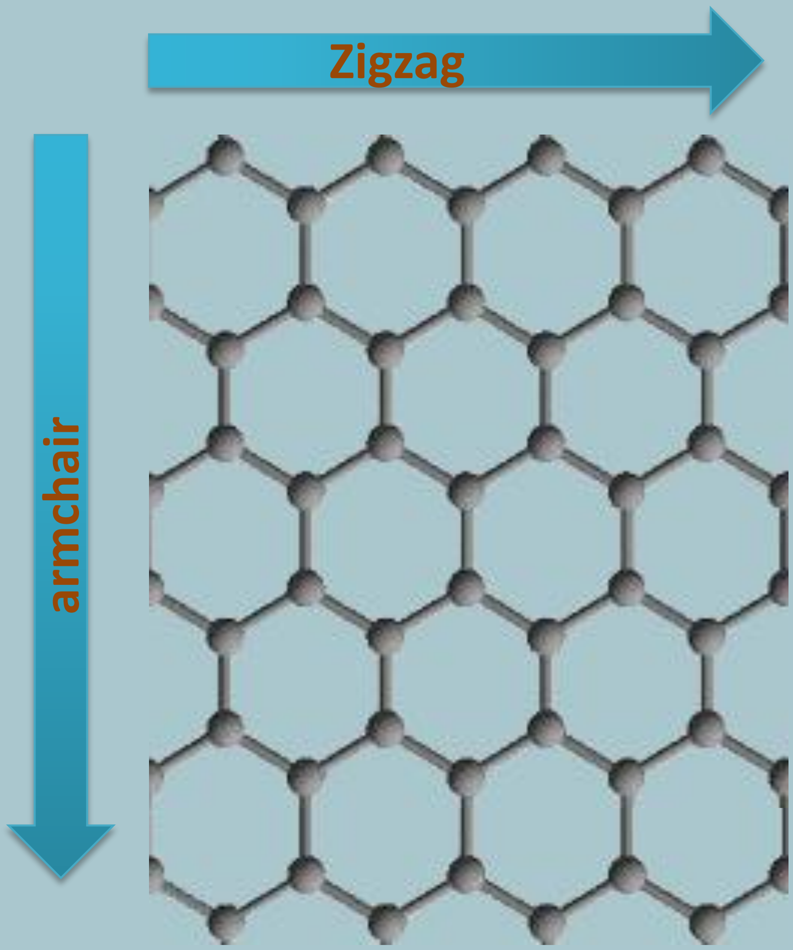
$$\epsilon l_B \le d/l_B,$$

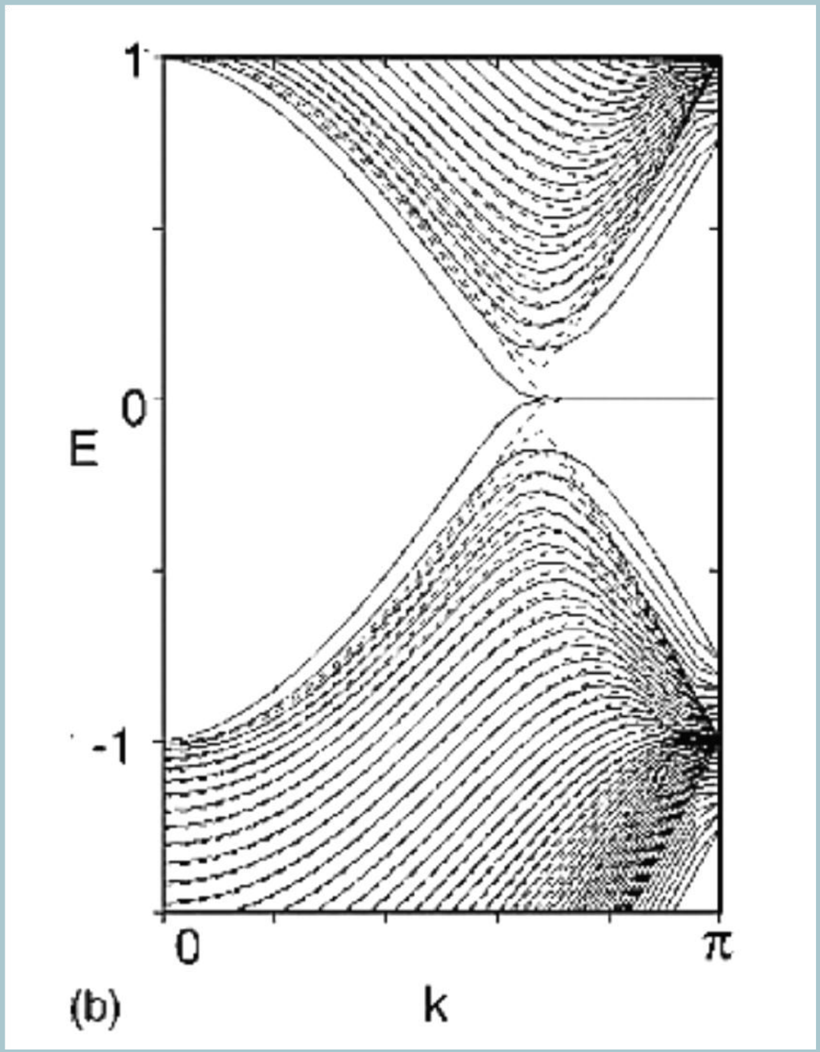


Transmission probability T for a magnetic barrier of width 2d

 A. De Martino et al., PRL **98,** 066802 (2007)

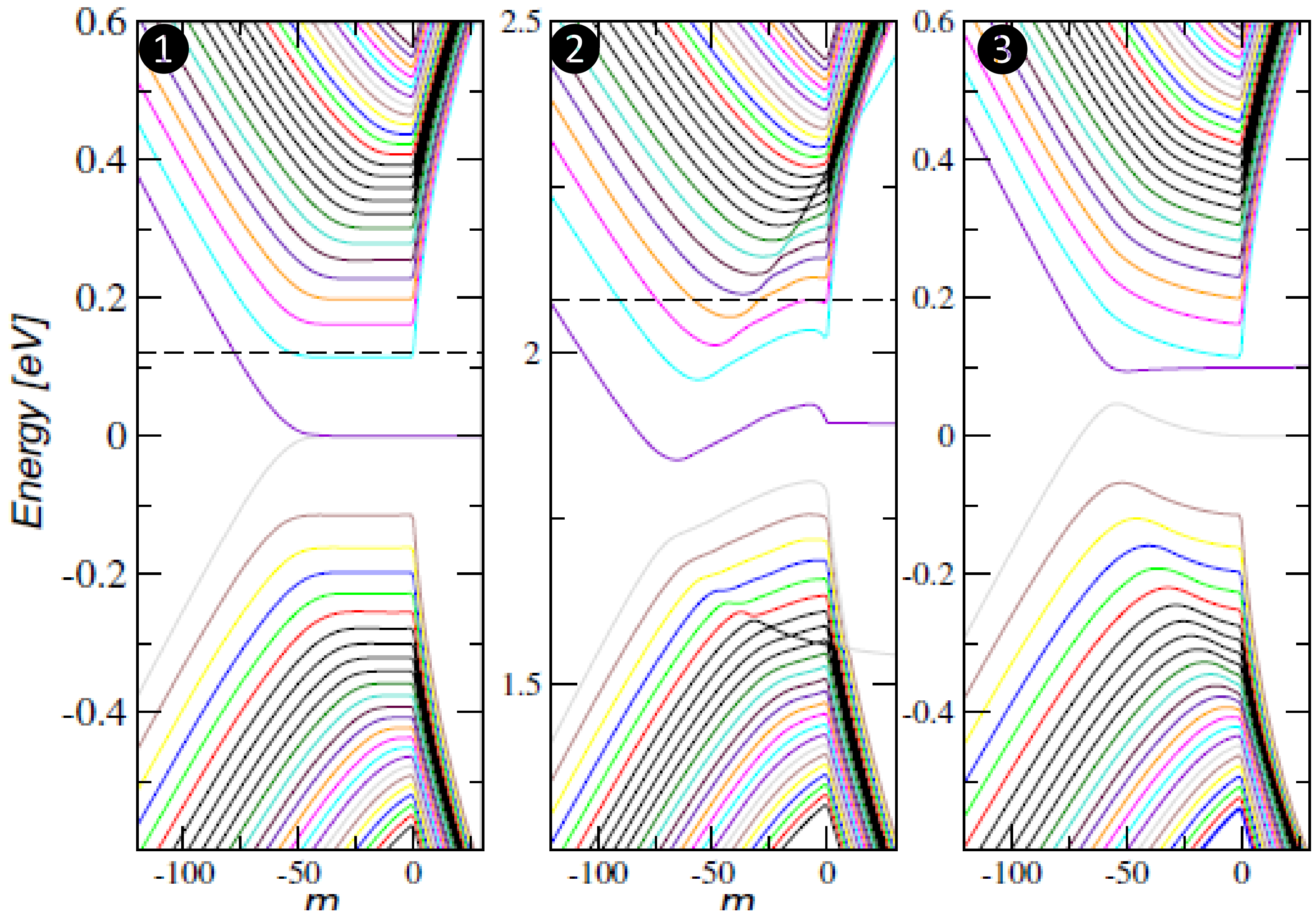
Zigzag states





K. Wakabayashi et al., PRB 59 8271 (1999)

circular dot in magnetic field (10 T)



Energy spectrum of a graphene quantum dot at *B* = 10 T

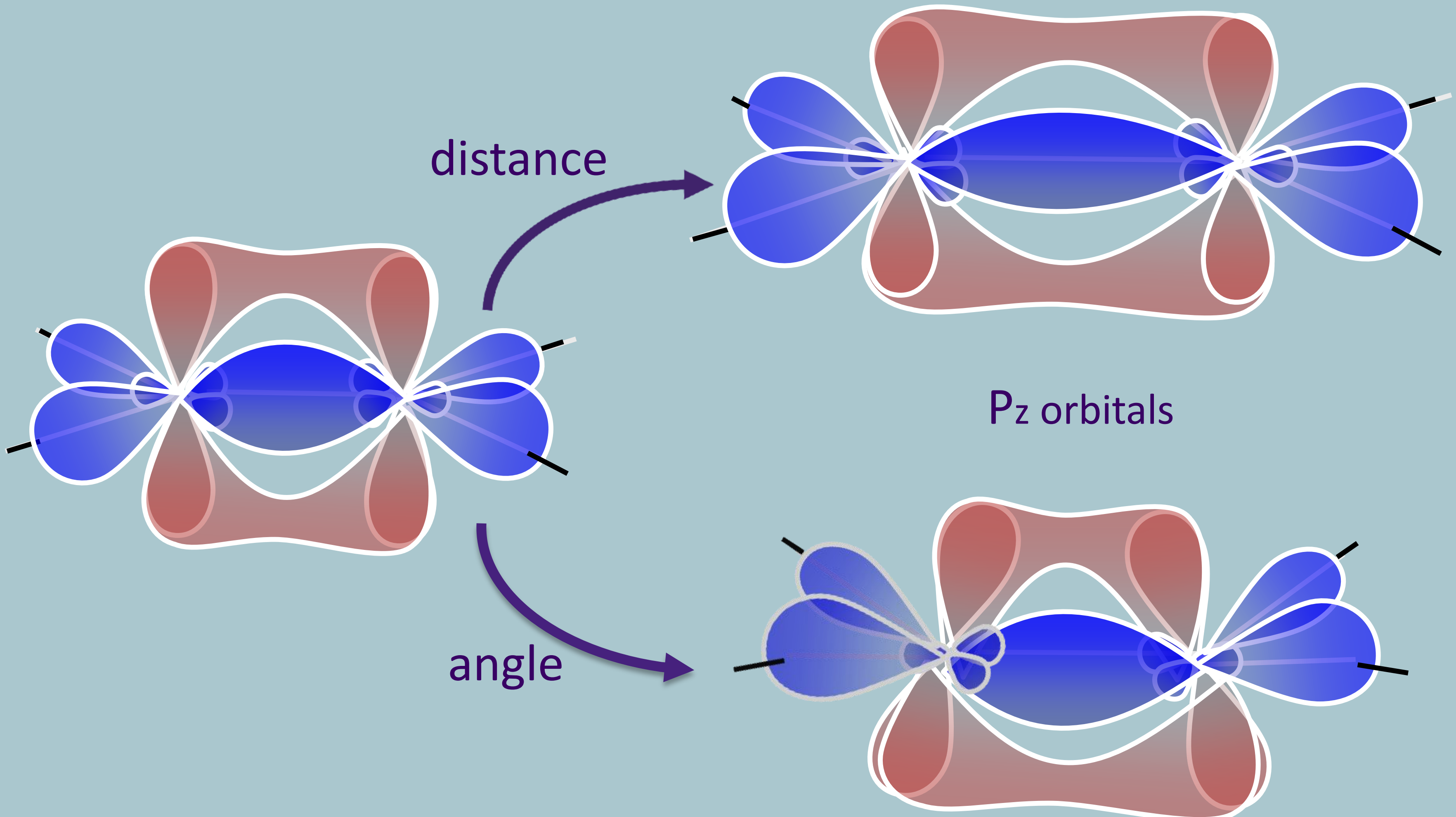
$V_{\mathrm{conf}}(r) = U_c(r/R)^4$

1. independent particle
2. Hartree bands
3. parabolic potential

N.M.R Peres et al., J. Phys.: Condens. Matter 21 344202 (2009)

Strain engineering

Disorder changes hopping energy by:



Hopping energies modification

$$H_{\mathrm{od}} = \sum_{i,j} \{\delta t_{ij}^{(ab)}(a_i^\dagger b_j + \mathrm{H.c.}) + \delta t_{ij}^{(aa)}(a_i^\dagger a_j + b_i^\dagger b_j)\},$$

$$H_{\mathrm{od}} = \int d^2 r \{\mathcal{A}(\mathbf{r}) a_1^\dagger(\mathbf{r}) b_1(\mathbf{r}) + \mathrm{H.c.} + \phi(\mathbf{r})[a_1^\dagger(\mathbf{r}) a_1(\mathbf{r}) + b_1^\dagger(\mathbf{r}) b_1(\mathbf{r})]\},$$

Change in bond length

$$\mathcal{A}(\mathbf{r}) = \sum_{\vec{\delta}_{ab}} \delta t^{(ab)}(\mathbf{r}) e^{-i\vec{\delta}_{ab}\cdot\mathbf{K}},$$

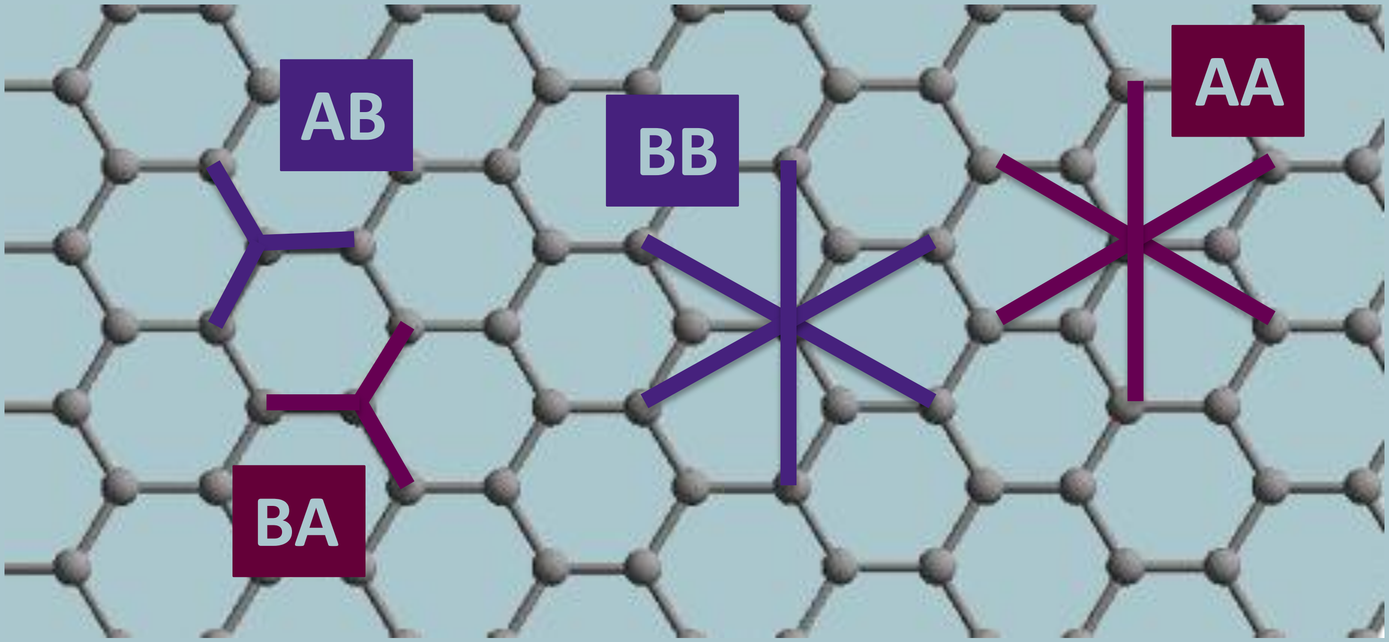
Change in unit cell area

$$\phi(\mathbf{r}) = \sum_{\vec{\delta}_{aa}} \delta t^{(aa)}(\mathbf{r}) e^{-i\vec{\delta}_{aa}\cdot\mathbf{K}}.$$

Inversion symmetry

$$\phi(r) = \phi^*(r)$$

$$A = A_x(r) + iA_y(r)$$



Time reversal is not broken

$$H_{\mathrm{od}} = \int d^2r[\hat{\Psi}_1^\dagger(\mathbf{r})\boldsymbol{\sigma}\cdot\vec{\mathcal{A}}(\mathbf{r})\hat{\Psi}_1(\mathbf{r}) + \phi(\mathbf{r})\hat{\Psi}_1^\dagger(\mathbf{r})\hat{\Psi}_1(\mathbf{r})],$$

$$A_x = c\frac{\beta t}{a}\left(u_{xx} - u_{yy}\right)$$

$$A_y = -c\frac{2\beta t}{a}u_{xy},$$

$$V(\vec{\mathbf{r}}) = g(u_{xx} + u_{yy}).$$

$$\beta = -\frac{\partial \ln t}{\partial \ln a} \simeq 2 \qquad g \approx 4\ \mathrm{eV} \qquad u_{\alpha\beta} = \frac{\partial_\alpha u_\beta + \partial_\beta u_\alpha}{2}$$

C depends on detailed model of chemical bonding

β and g are the coupling to acoustical wave in graphene

M.A.H. Vozmedianoa et al., arXiv:1003.5179v2 (2010)

strong pseudomagnetic field which guides electrons

Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles

N. Levy,[1,2]*† S. A. Burke,[1]*‡ K. L. Meaker,[1] M. Panlasigui,[1] A. Zettl,[1,2] F. Guinea,[3] A. H. Castro Neto,[4] M. F. Crommie[1,2]§

Recent theoretical proposals suggest that strain can be used to engineer graphene electronic states through the creation of a pseudo–magnetic field. This effect is unique to graphene because of its massless Dirac fermion-like band structure and particular lattice symmetry (C_{3v}). Here, we present experimental spectroscopic measurements by scanning tunneling microscopy of highly strained nanobubbles that form when graphene is grown on a platinum (111) surface. The nanobubbles exhibit Landau levels that form in the presence of strain-induced pseudo–magnetic fields greater than 300 tesla. This demonstration of enormous pseudo–magnetic fields opens the door to both the study of charge carriers in previously inaccessible high magnetic field regimes and deliberate mechanical control over electronic structure in graphene or so-called "strain engineering."

Graphene, a single atomic layer of carbon, displays remarkable electronic and mechanical properties (*1*, *2*). Many of graphene's distinctive properties arise from a linear band dispersion at low carrier energies (*3*) that leads to Dirac-like behavior within the two-dimensional (2D) honeycomb lattice—charge (*1*). An intriguing recent prediction is that a distortion of the graphene lattice should create large, nearly uniform pseudo–magnetic fields and give rise to a pseudo–quantum Hall effect (*4*). Whereas an elastic strain can be expected to induce a shift in the Dirac point energy from local changes in electron density, it is also predicted to induce changes in the electron-hopping amplitude between carbon atoms (*5*). This strain-induced gauge field can give rise to large pseudo–magnetic fields (B_s) for appropriately selected geometries of the applied strain (*1*, *6*). In such situations, the charge carriers in graphene are expected to circulate as if under the influence of an applied out-of-plane magnetic field (*7*–*10*). It has recently been proposed that a modest strain field with triangular symmetry will give approximately uniform, quantizing B_s upward of tens of tesla (*4*).

Here, we report the measurement of Landau levels (LLs) arising from giant strain-induced pseudo–magnetic fields in highly strained graphene nanobubbles grown on the Pt(111) surface. Lan-

[1]Department of Physics, University of California Berkeley, Berkeley, CA 94720, USA. [2]Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA. [3]Instituto de Ciencia de Materiales de Madrid ... rid 28049, Spain. [4]Department of Physi... ston, MA 02215, USA.
*T... gy,
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couver,
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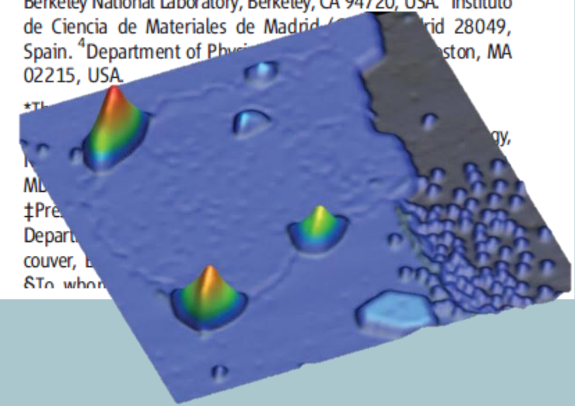
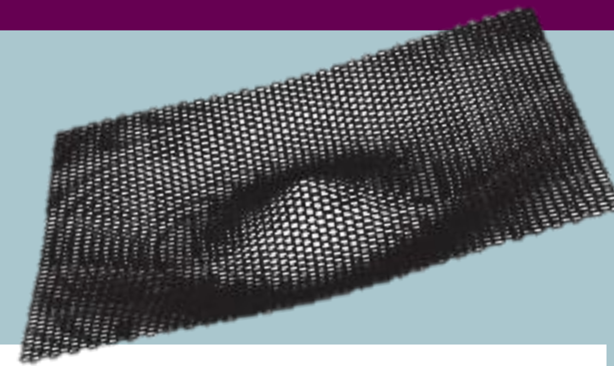


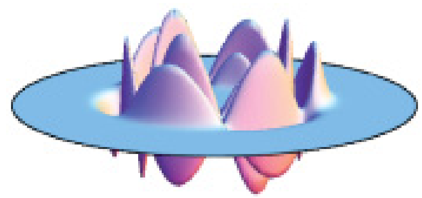
N. Levy et al., SCIENCE VOL 329 544 (2010)

ring-shaped Gaussian deformation

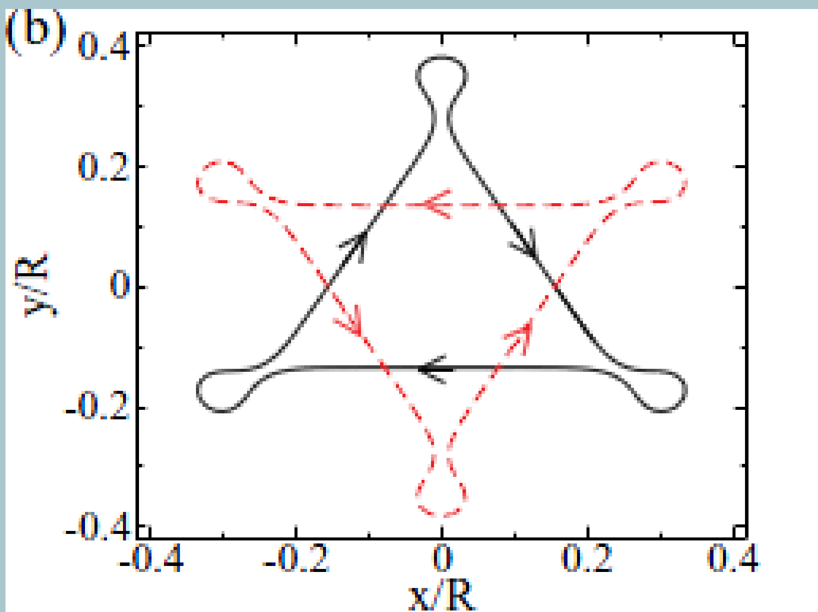


$$u_z(\mathbf{r}) = Ae^{-\frac{(\sqrt{x^2+y^2}-c)^2}{b^2}}$$

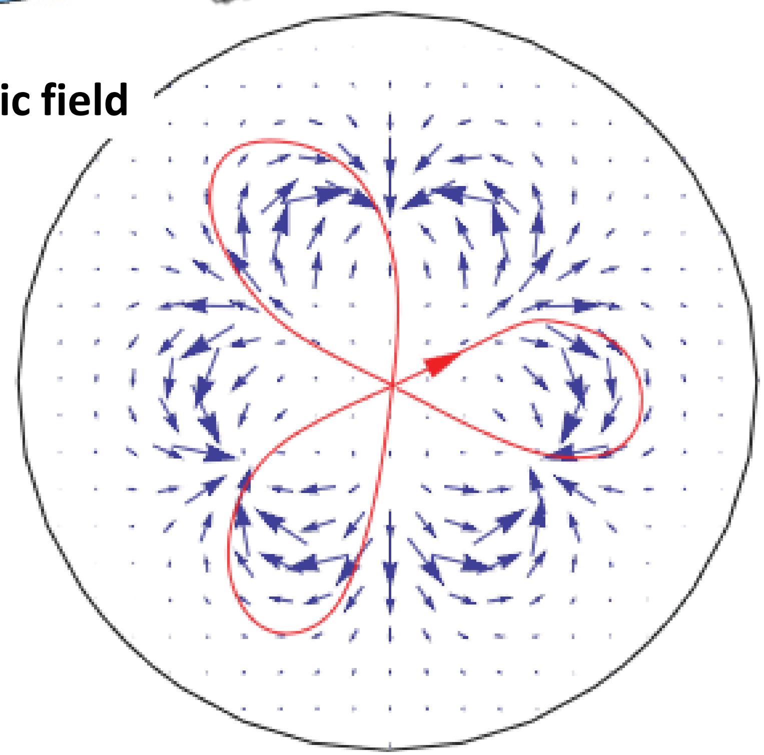
$$B_{ps} \propto \sin 3\theta$$



Pseudo magnetic field



Classical trajectories

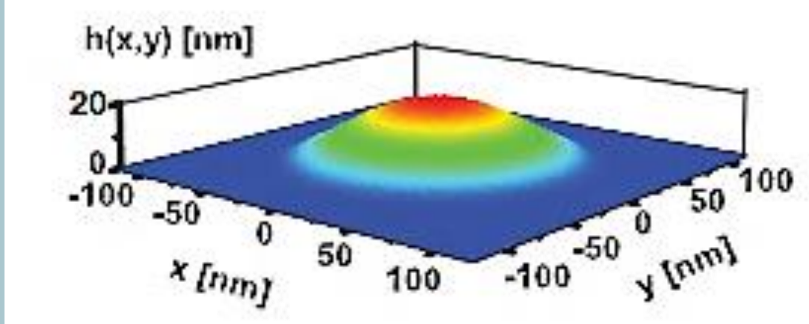


Current density

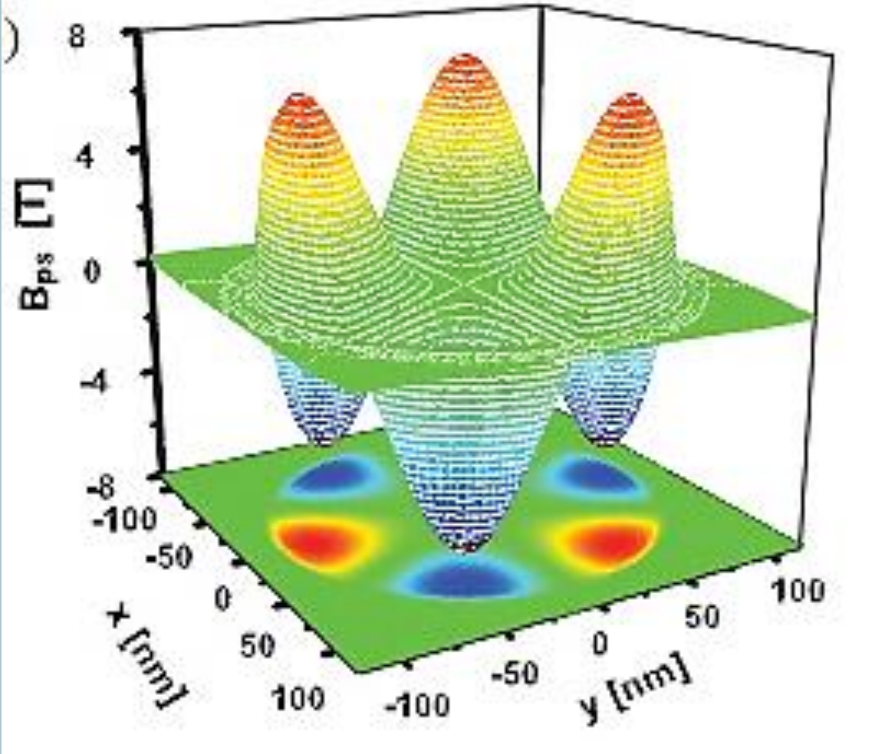
G. M. M. Wakker et al., PHYSICAL REVIEW B 84, 195427 (2011)

rotationally symmetric strain

Made by
atomic force microscopy (AFM) tip
or by a homogeneous gas pressure



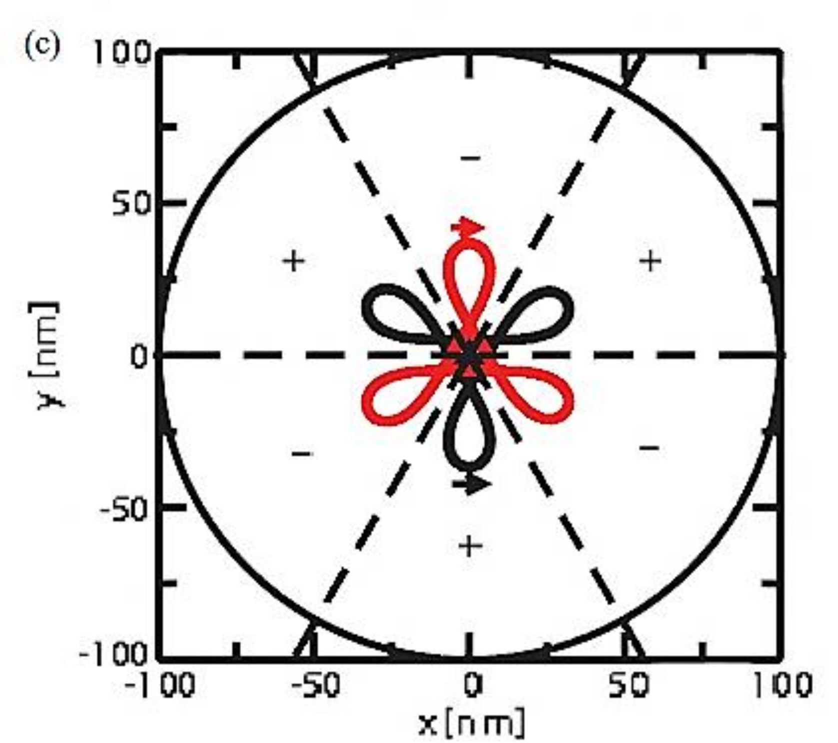
vertical displacement



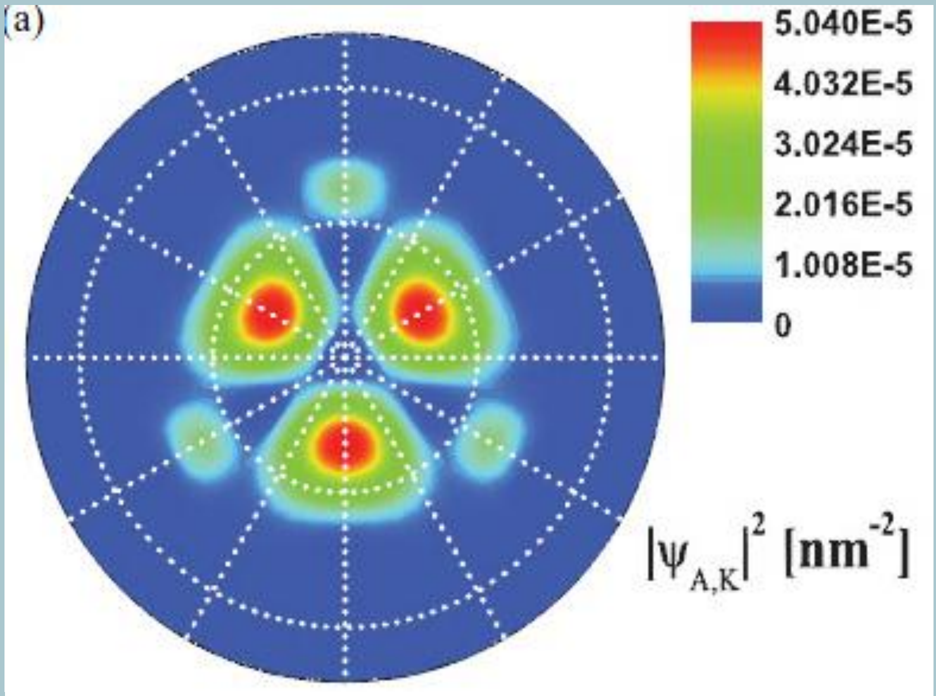
Pseudo magnetic field

 K.J Kim et al., PHYSICAL REVIEW B 84, 081401(R) (2011)

rotationally symmetric strain



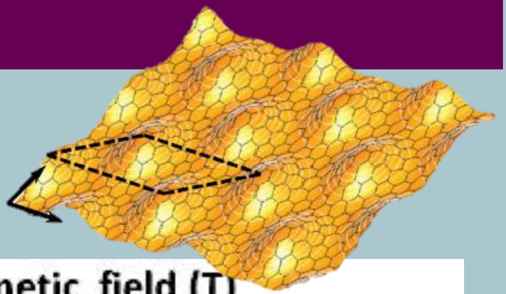
Classical trajectories

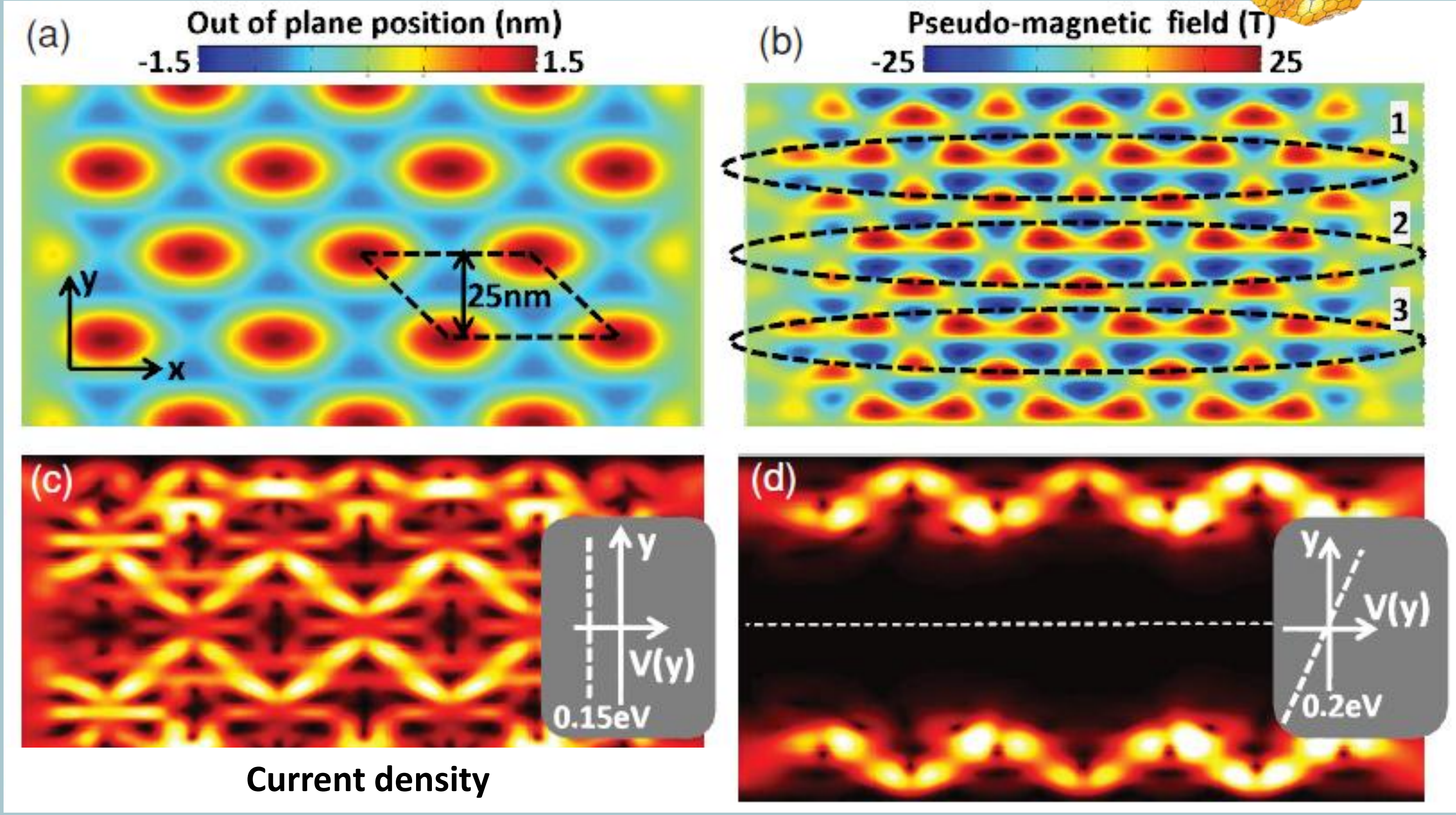


Probability density

 K.J Kim et al., PHYSICAL REVIEW B 84, 081401(R) (2011)

Tunable gap in strained graphene





Current density

 T. Low et al., PHYSICAL REVIEW B 83, 195436 (2011)

Conclusion

- Graphene is a promising candidate for nano-electronic applications.
- Confinement is achievable via strain engineering or external fields.

Thank you