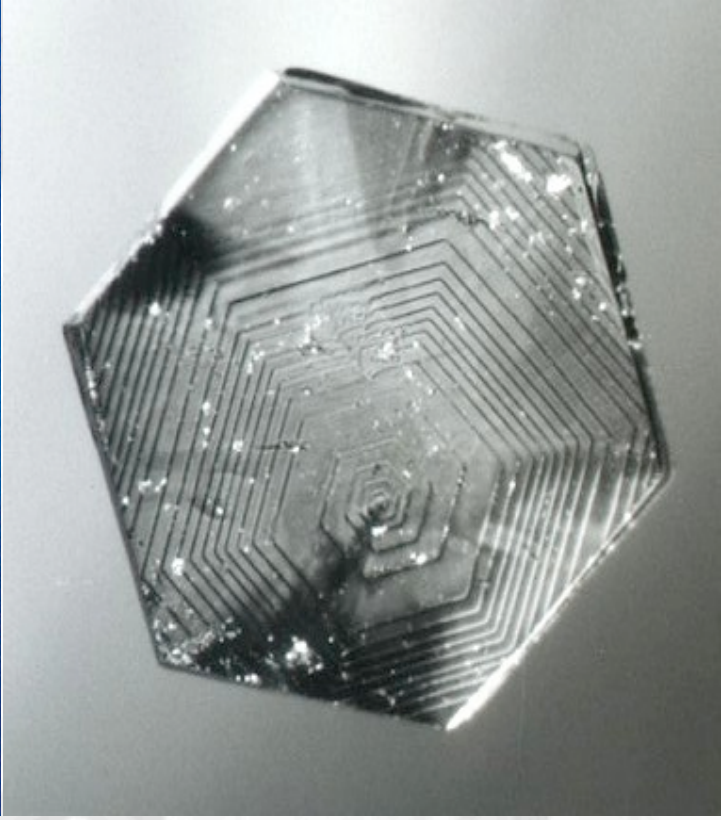
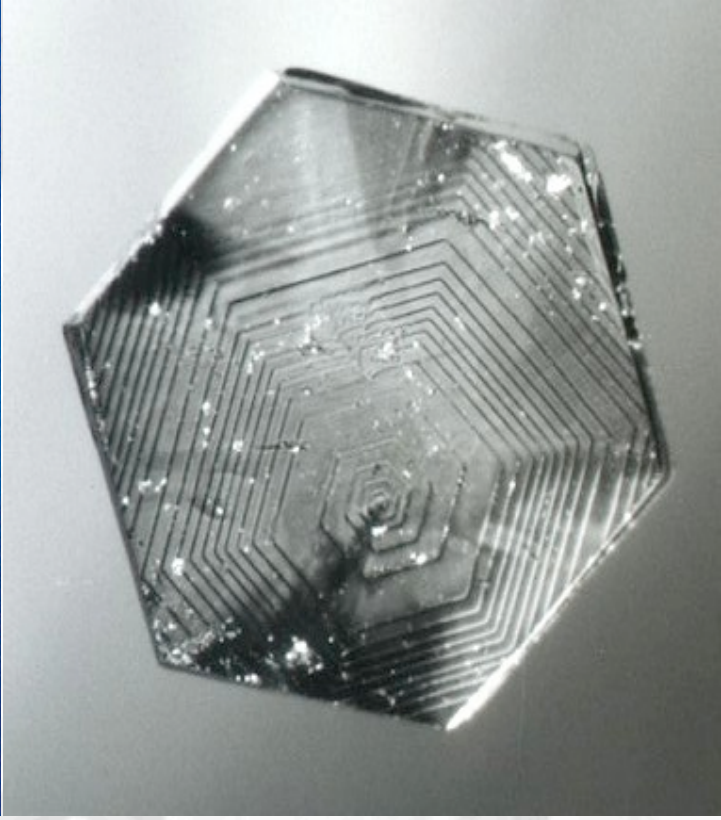
Antonio H. Castro Neto

Funding by:

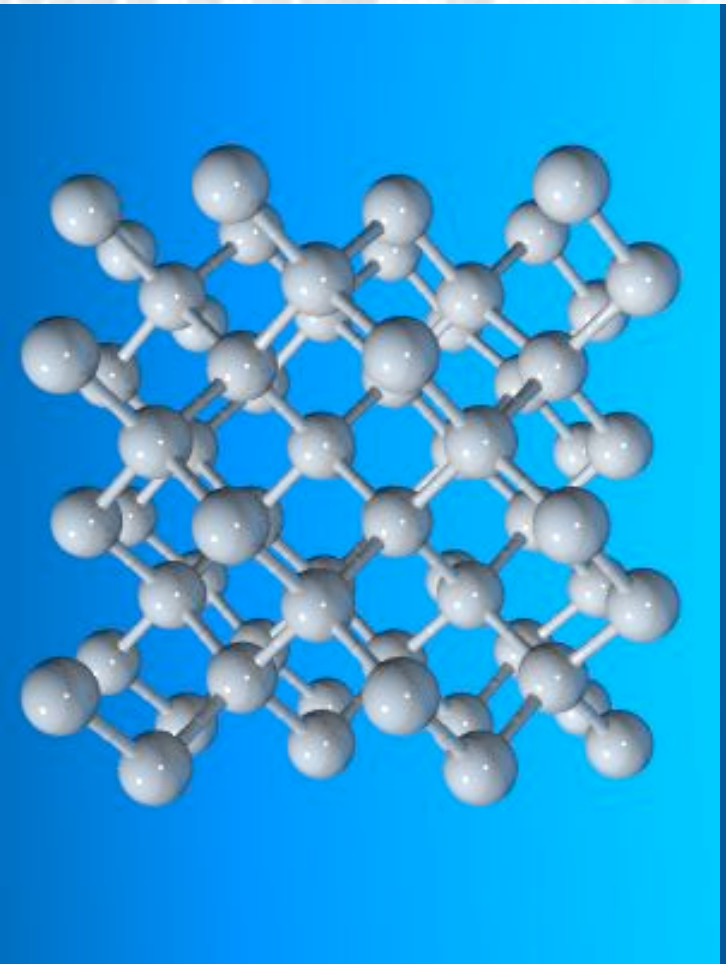
The carbon new age

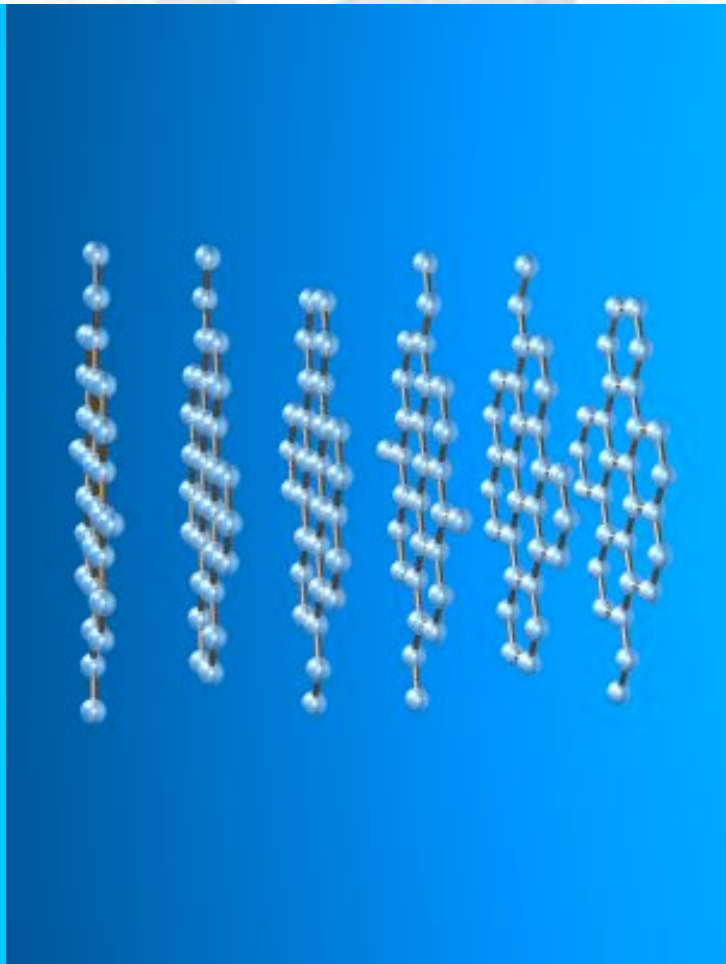


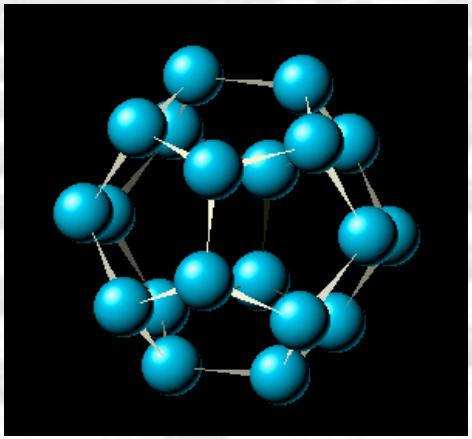
Diamond **Graphite**



Diamond **Graphite**







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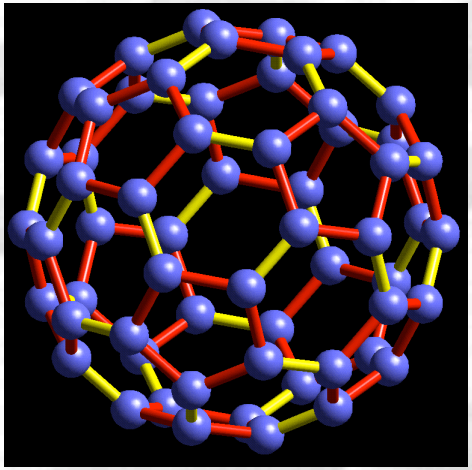
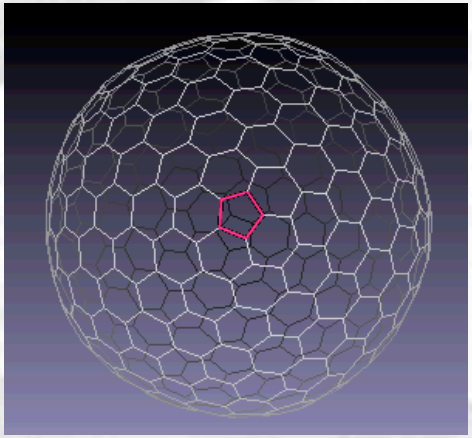


C60

Fullerenes or Buckyballs
zero dimensional



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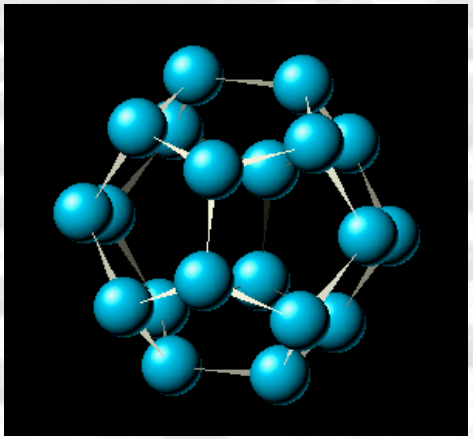

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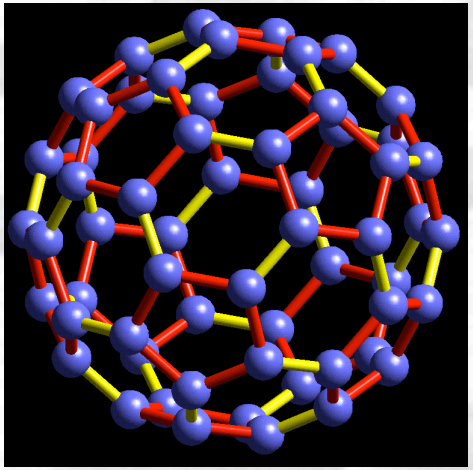

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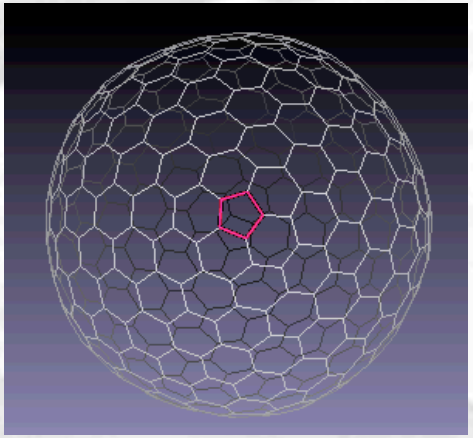

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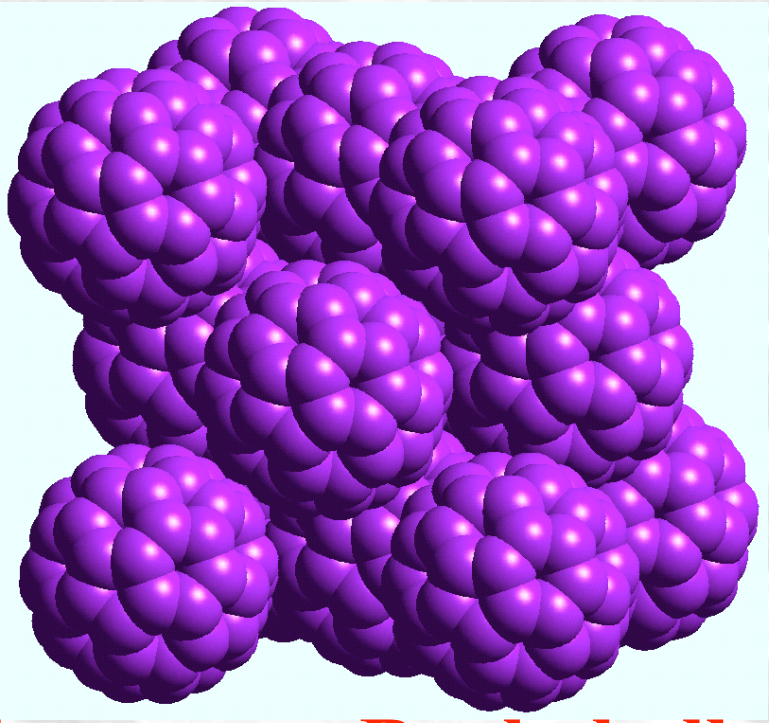
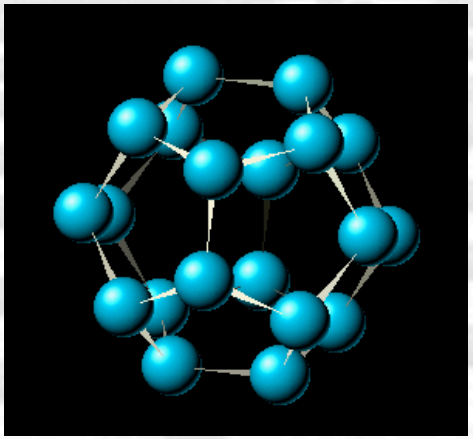


Fullerenes or Buckyballs
zero dimensional



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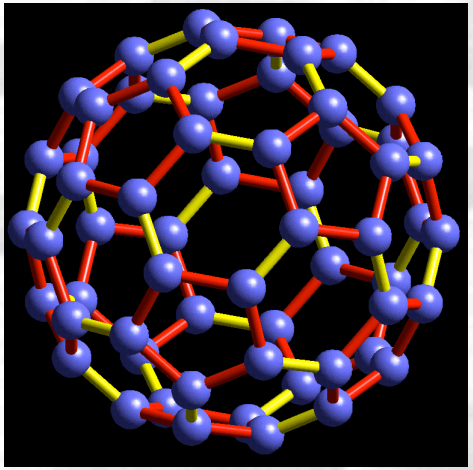

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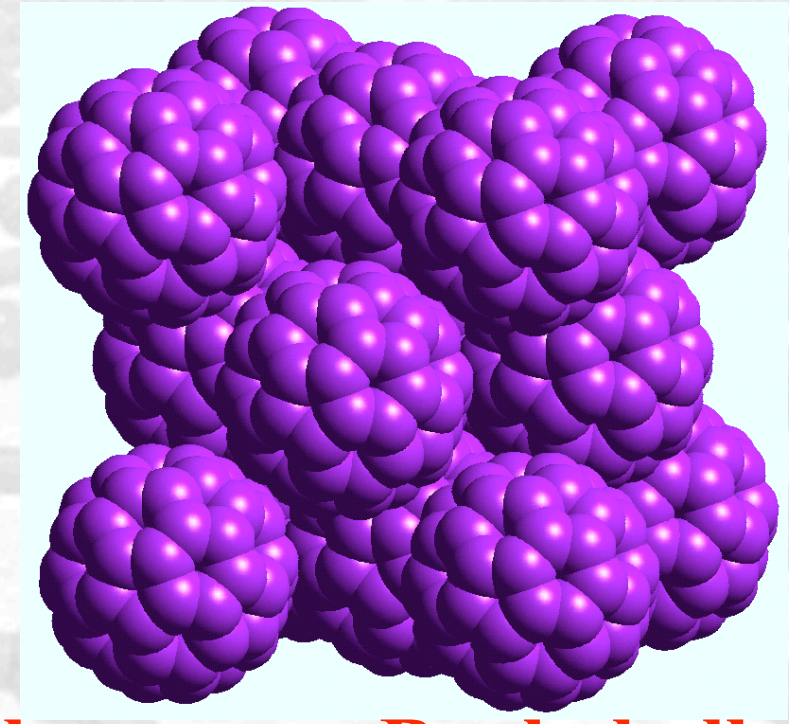
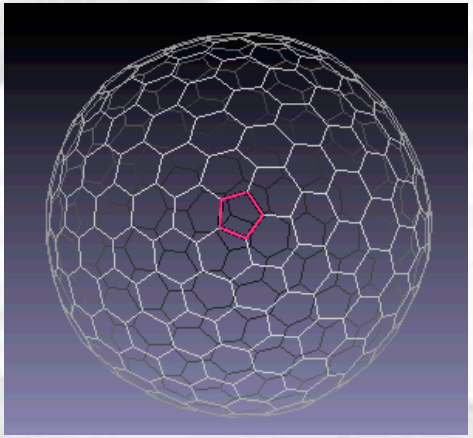


Fullerenes or Buckyballs
zero dimensional



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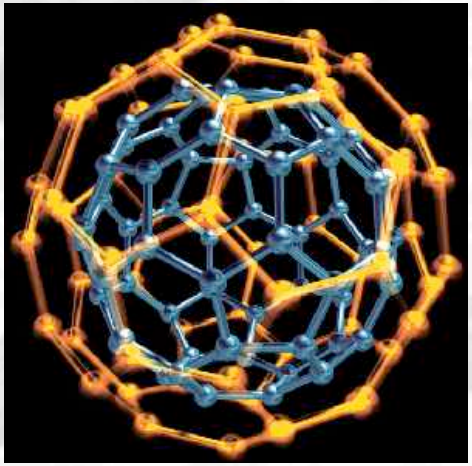

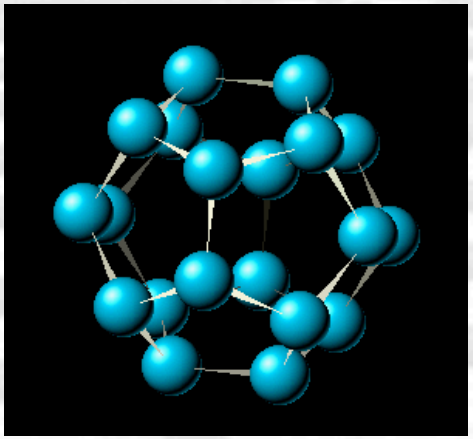

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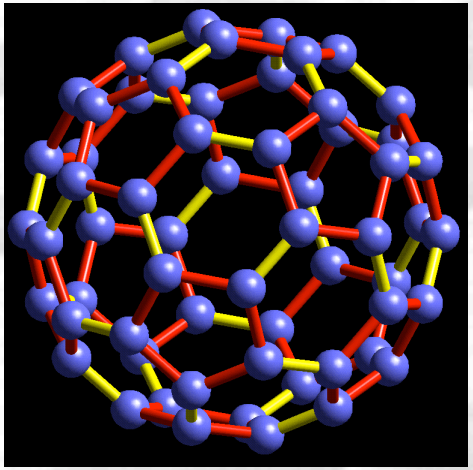

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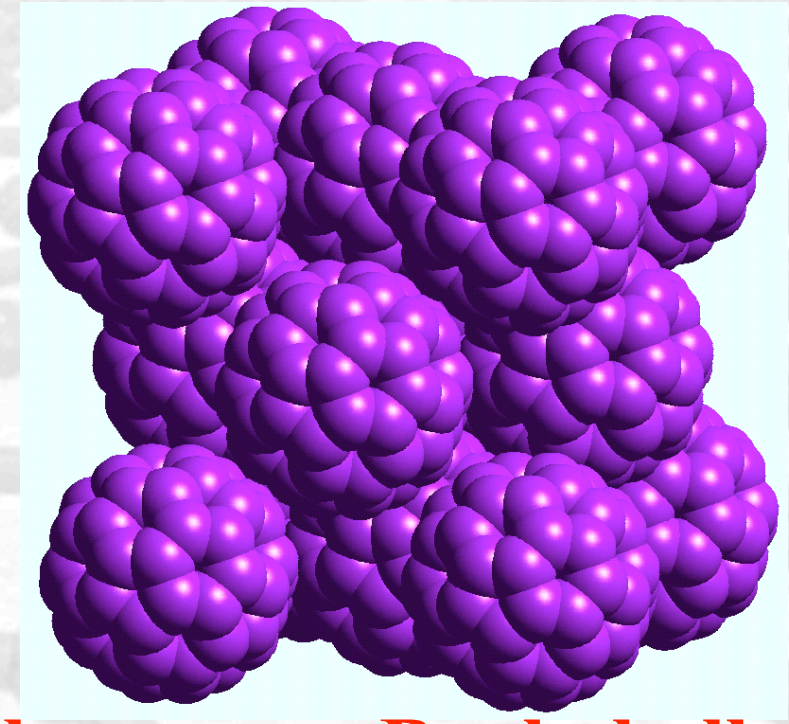

Fullerenes or Buckyballs
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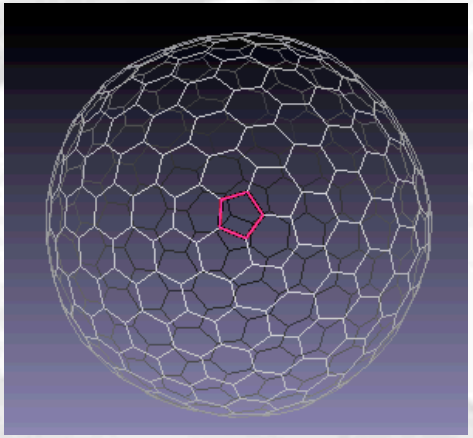

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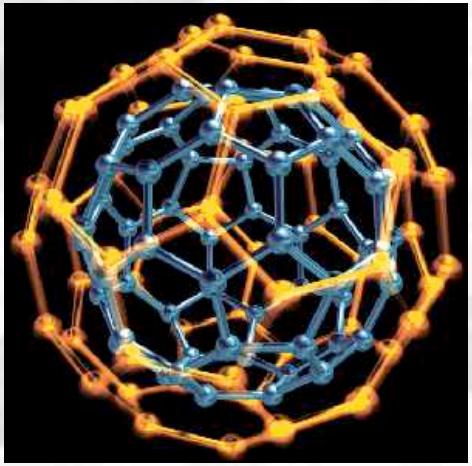
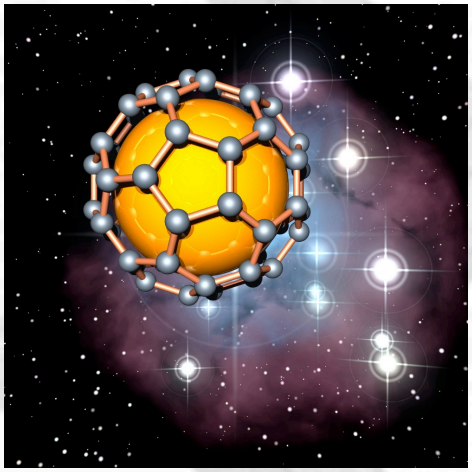
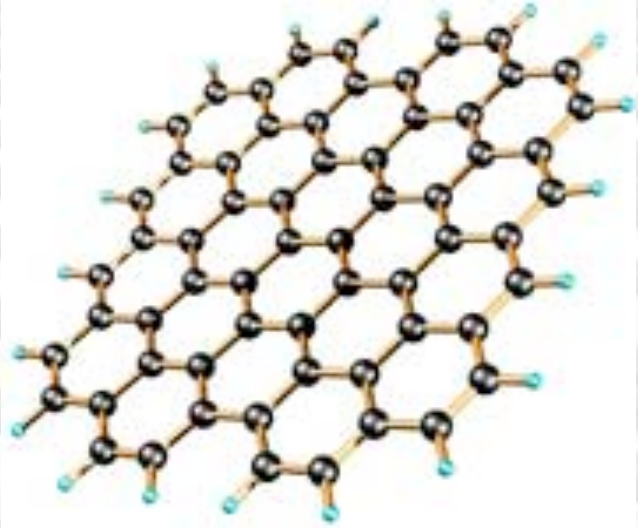
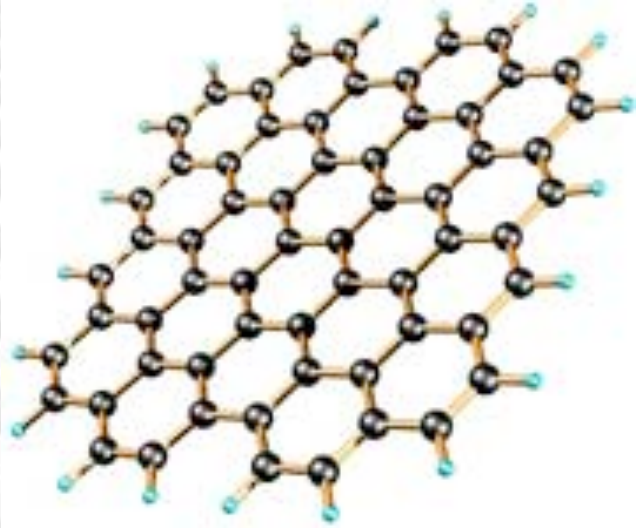




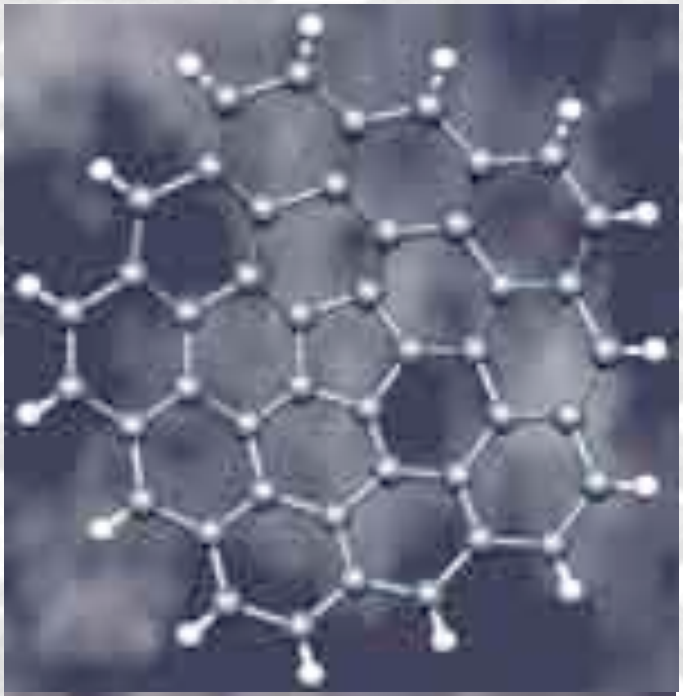
The making of a fullerene

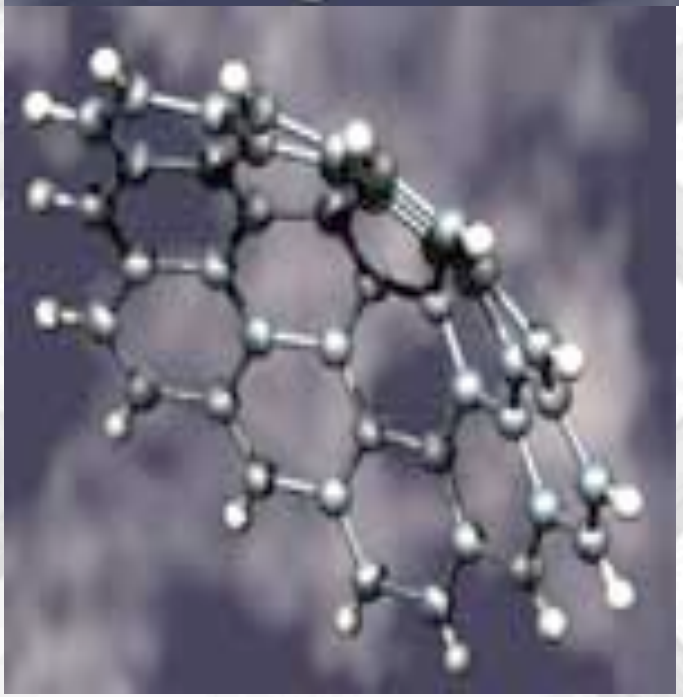


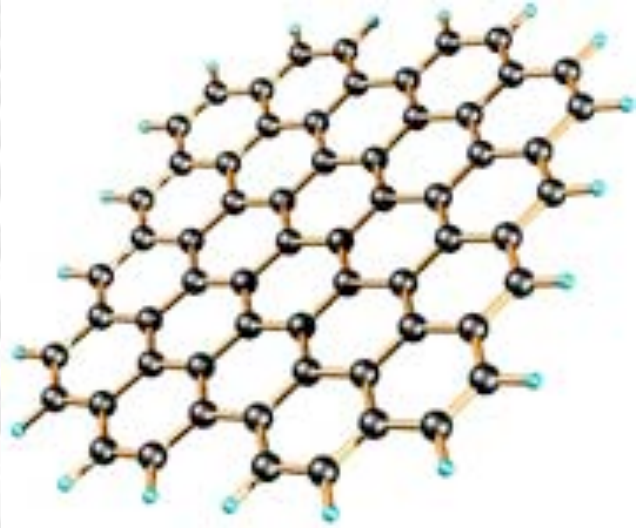
1. Take graphene



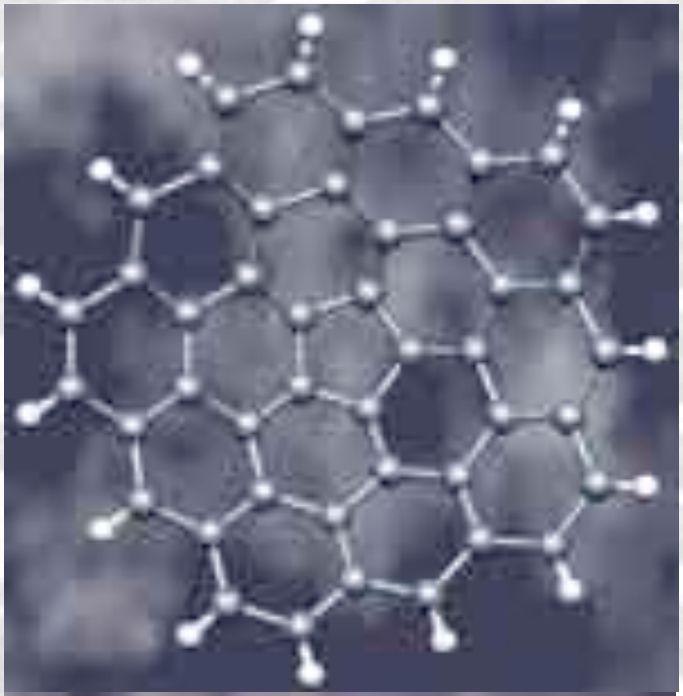
2. Add a pentagon

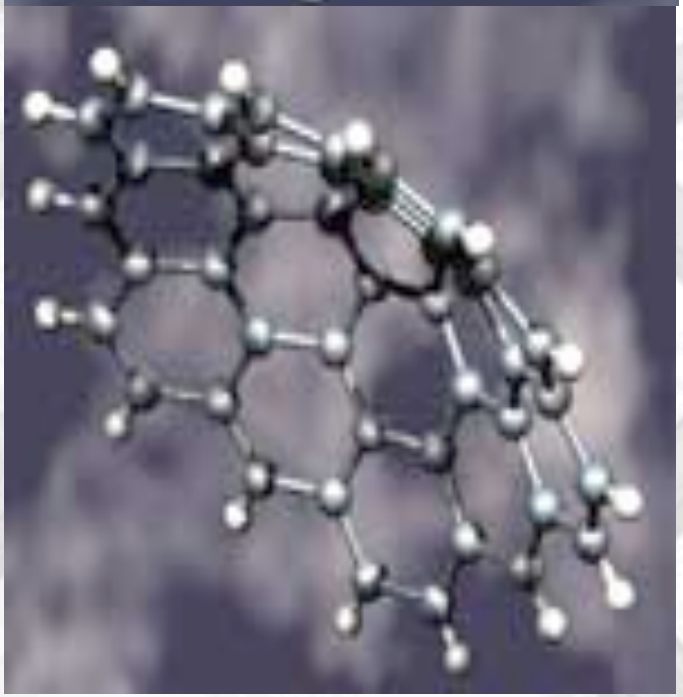


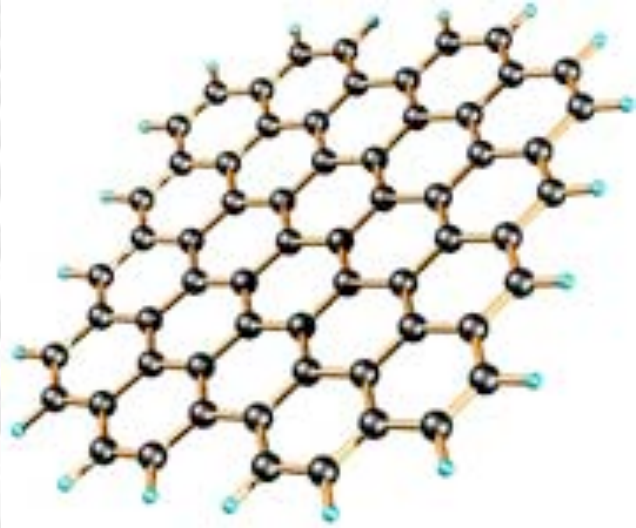




3. Add a few more!







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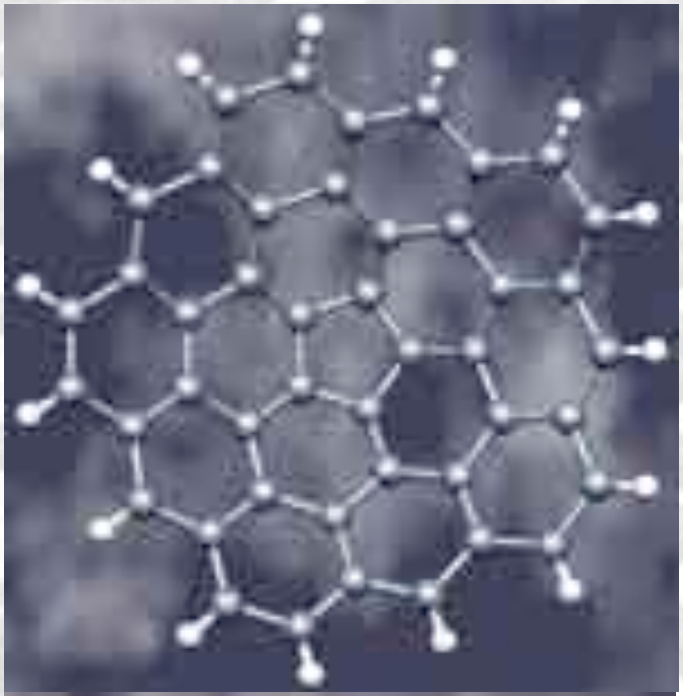
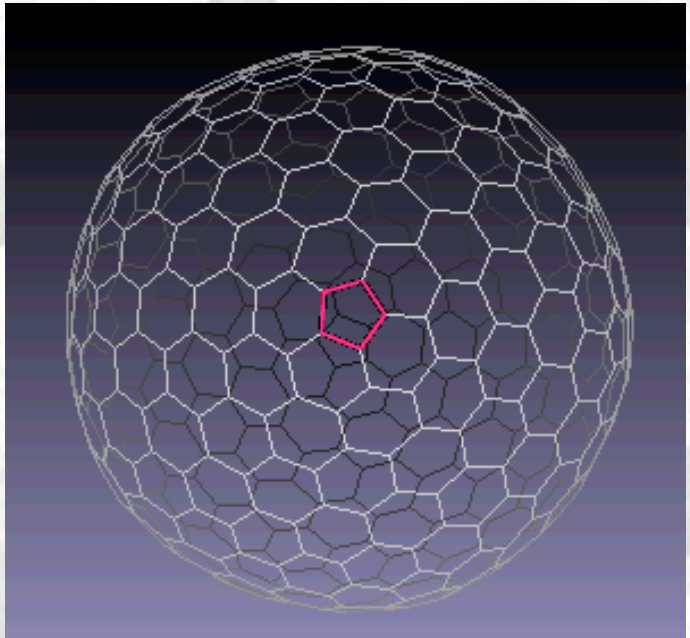
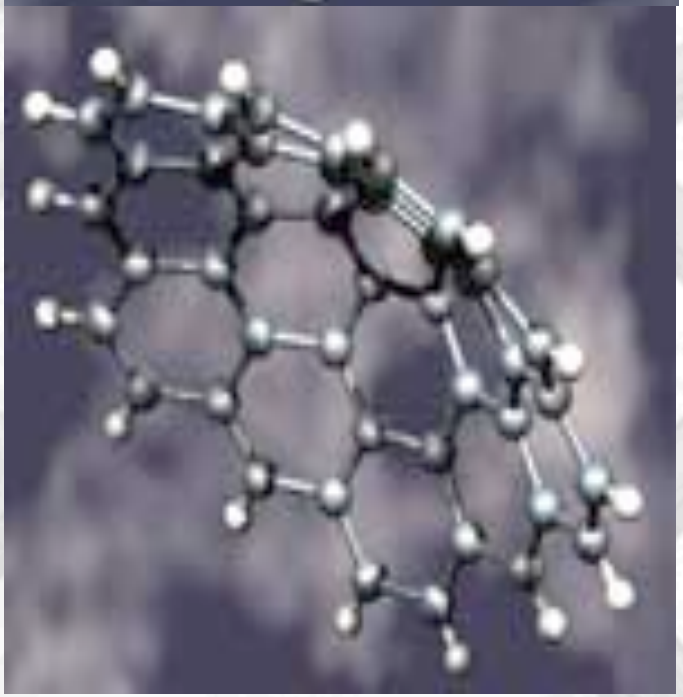
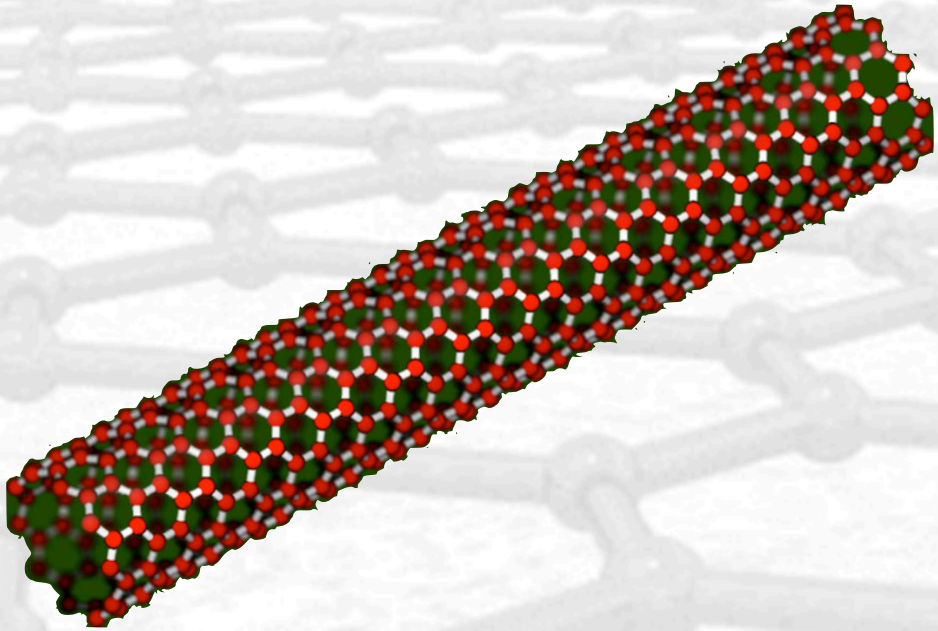
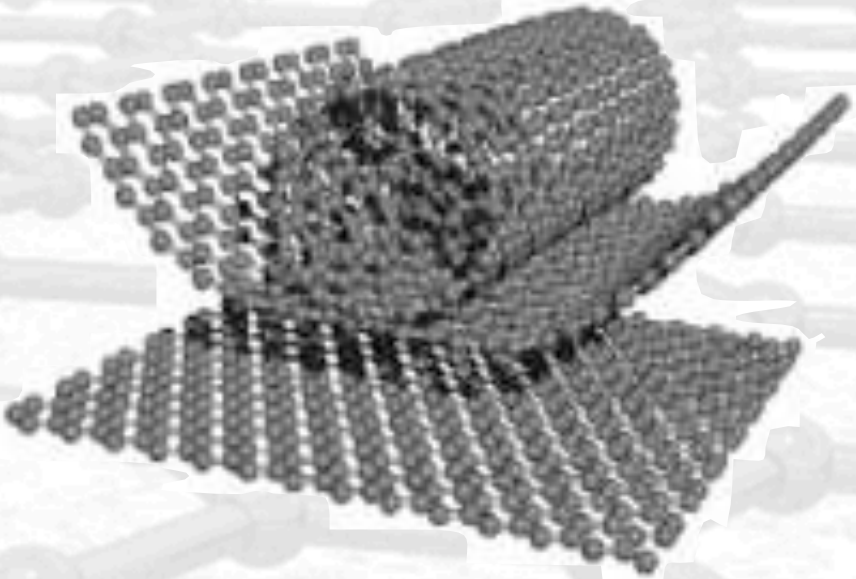


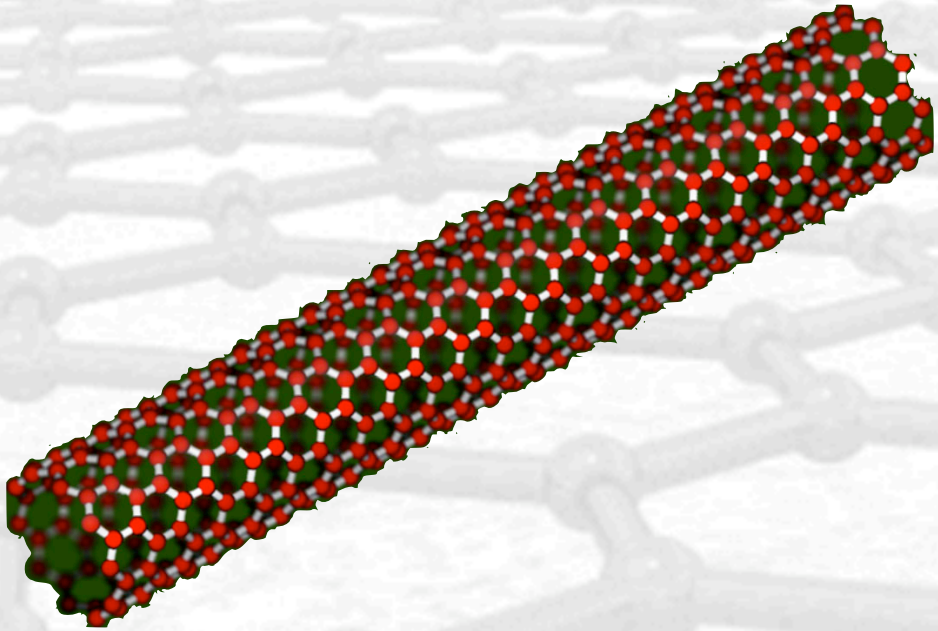


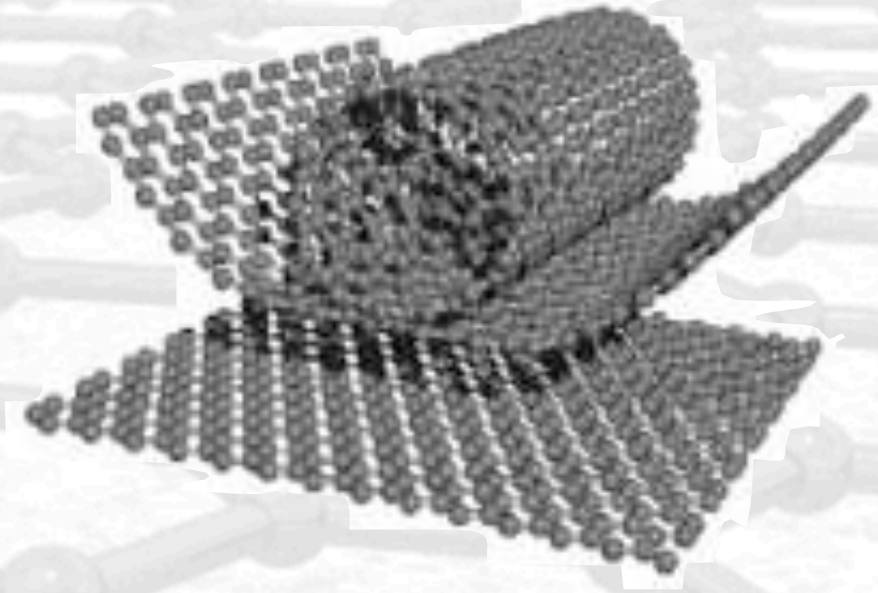


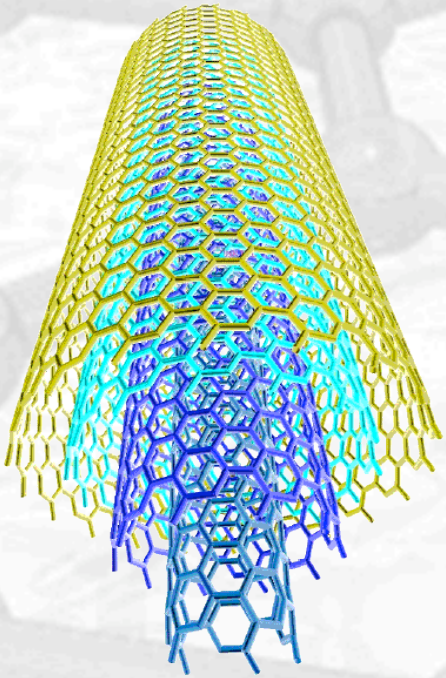


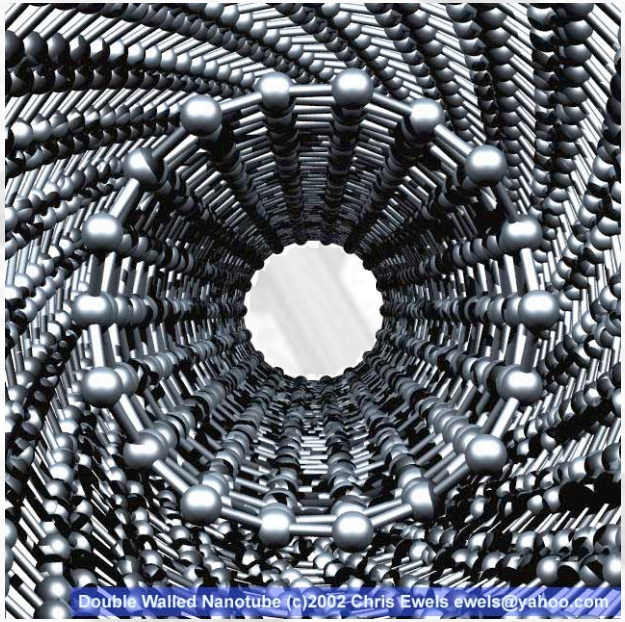


Carbon Nanotubes: one dimensional



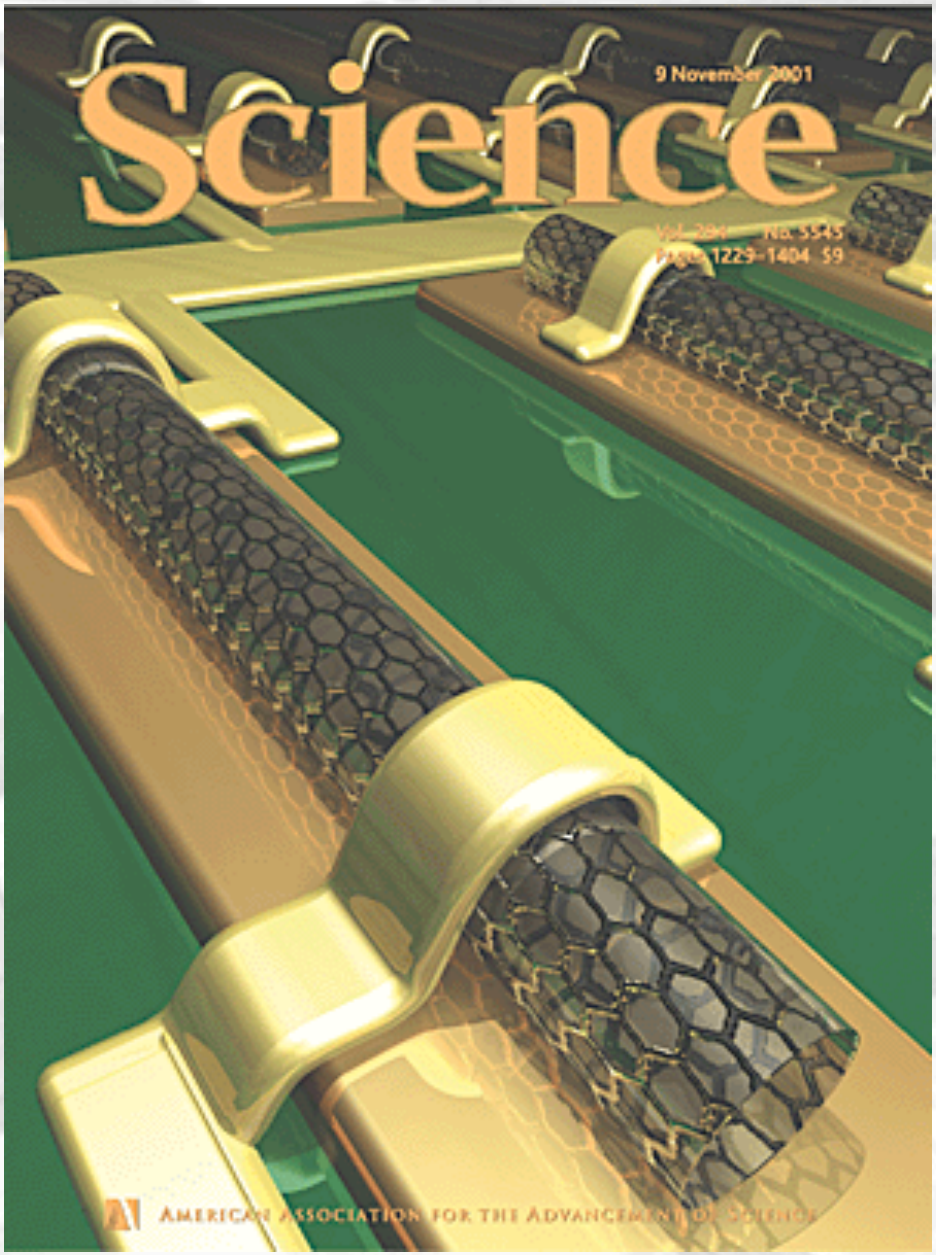




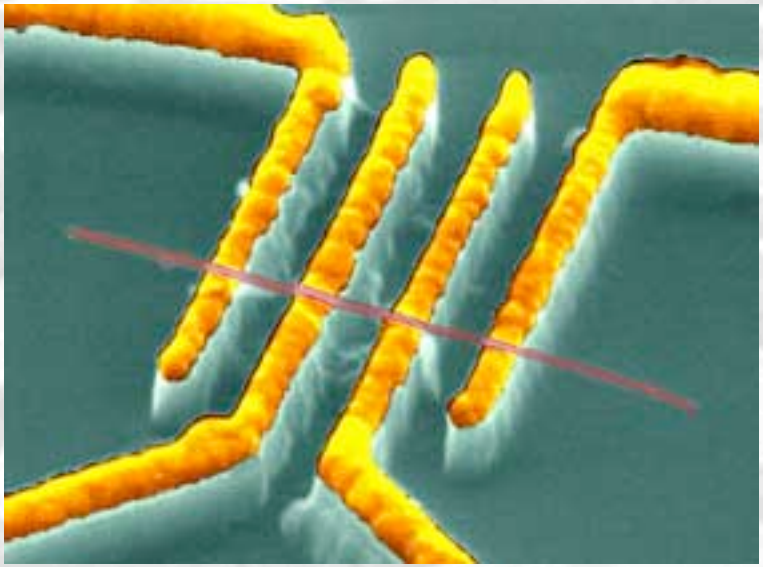


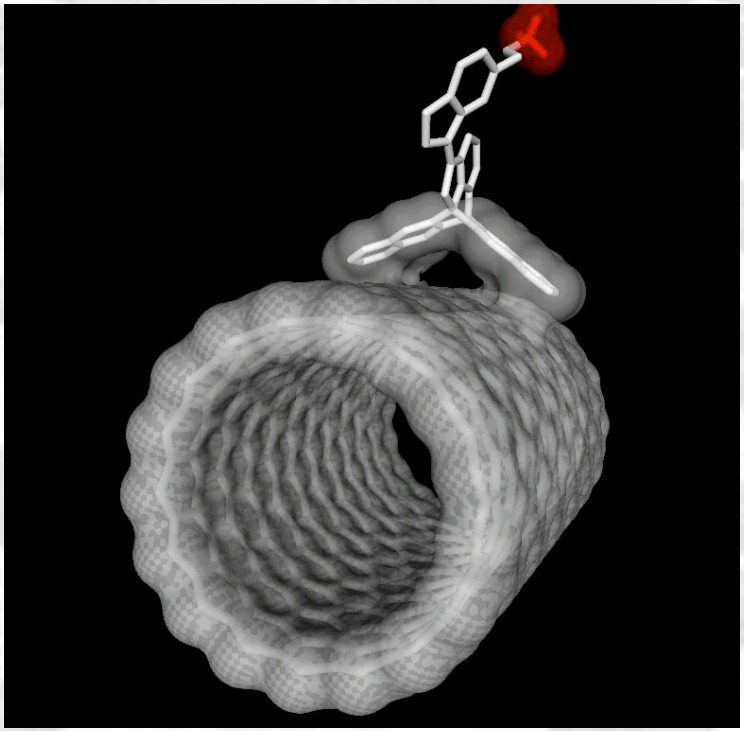
Carbon Nanotubes: one dimensional

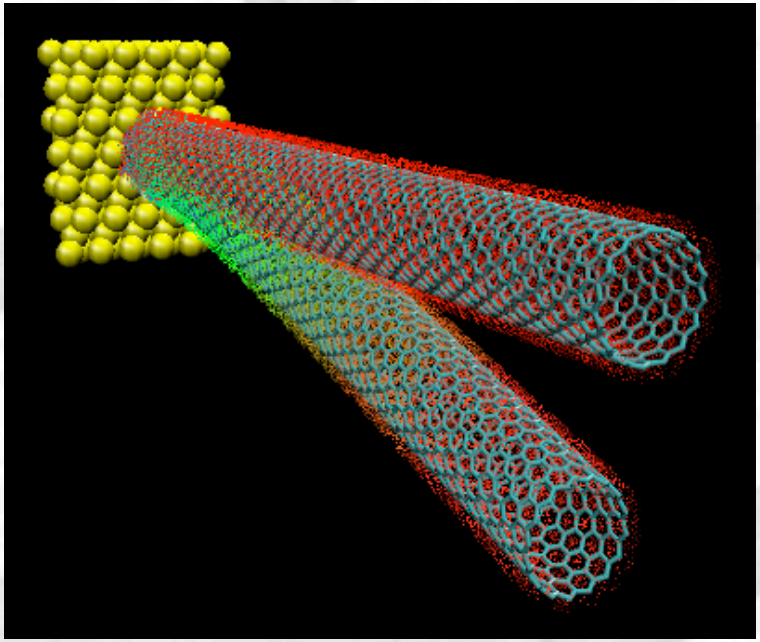
Beautiful… and useful !



Beautiful… and useful !

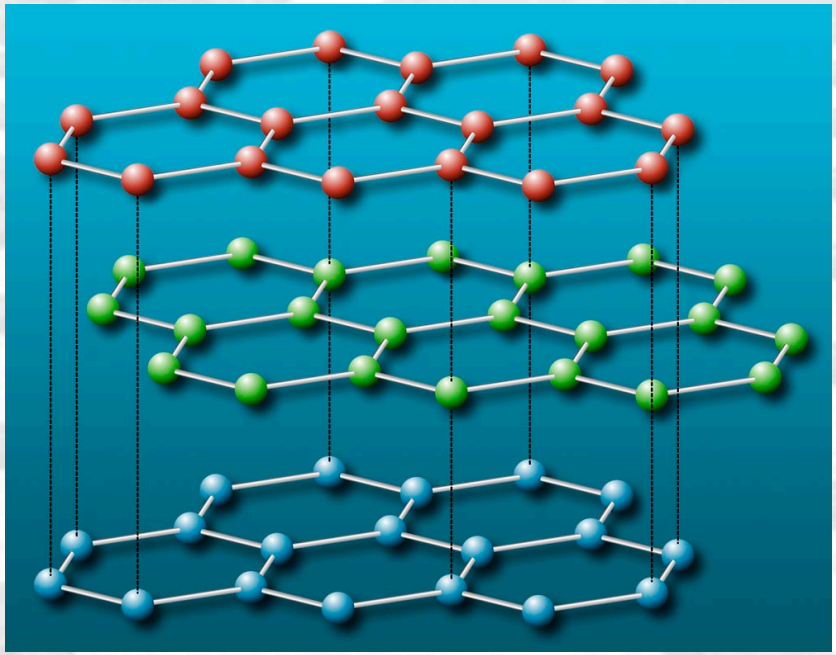






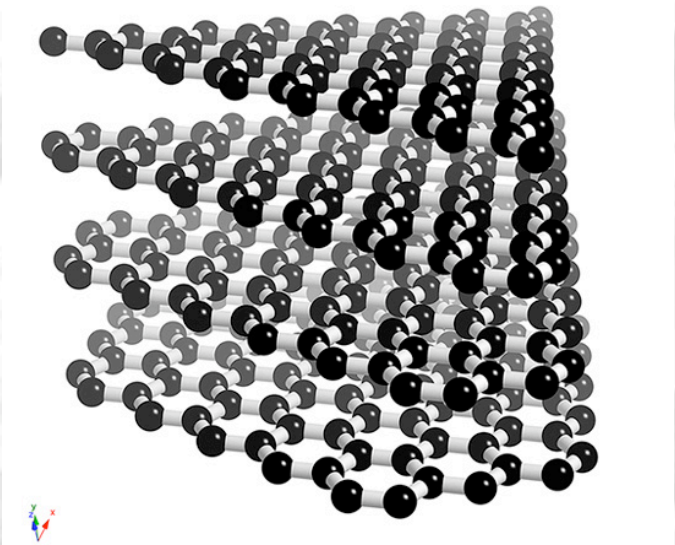
Microscopic electric cables
Nanomechanical Resonator
Chemical sensors

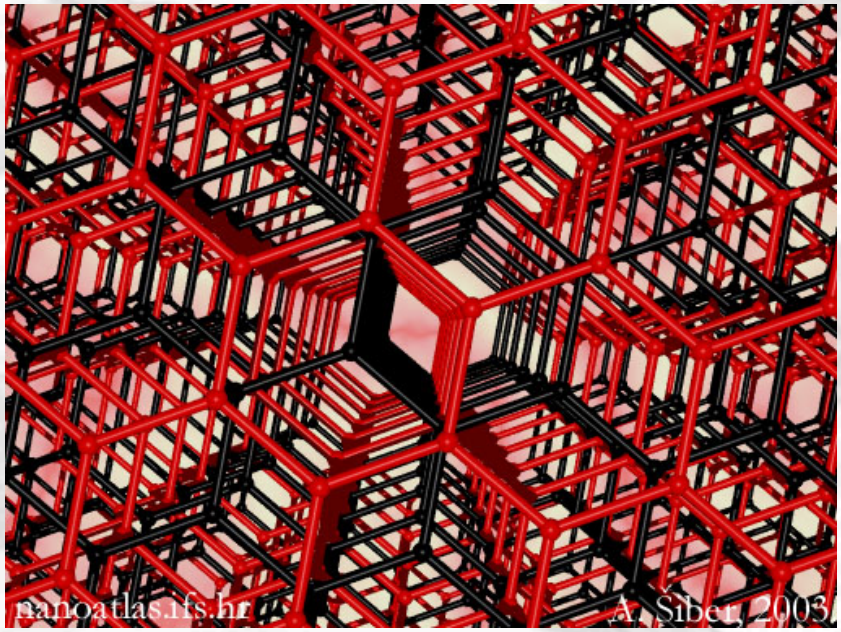
Graphite



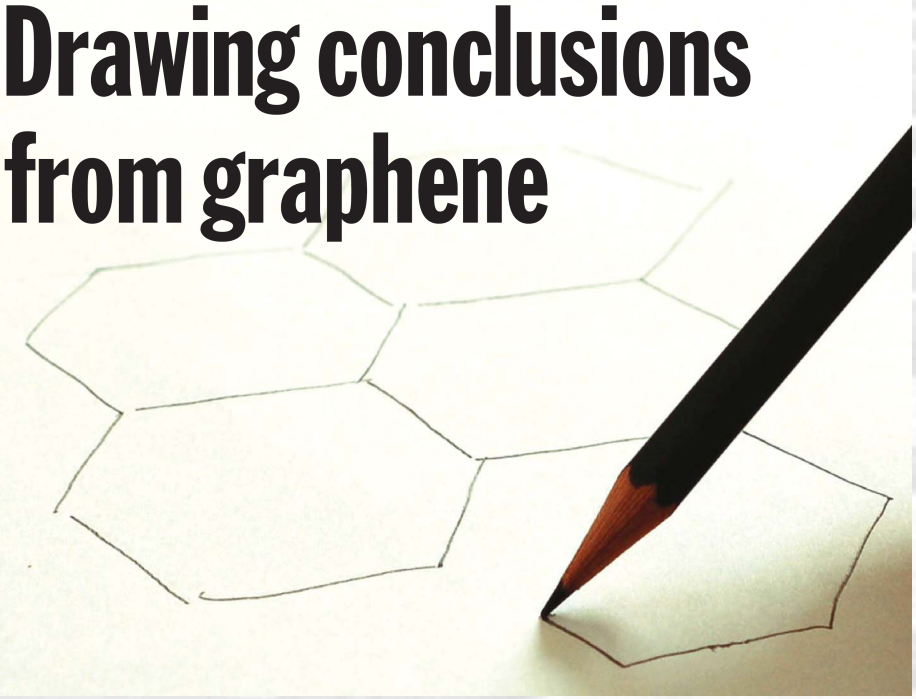
Graphite

Stacked graphene!

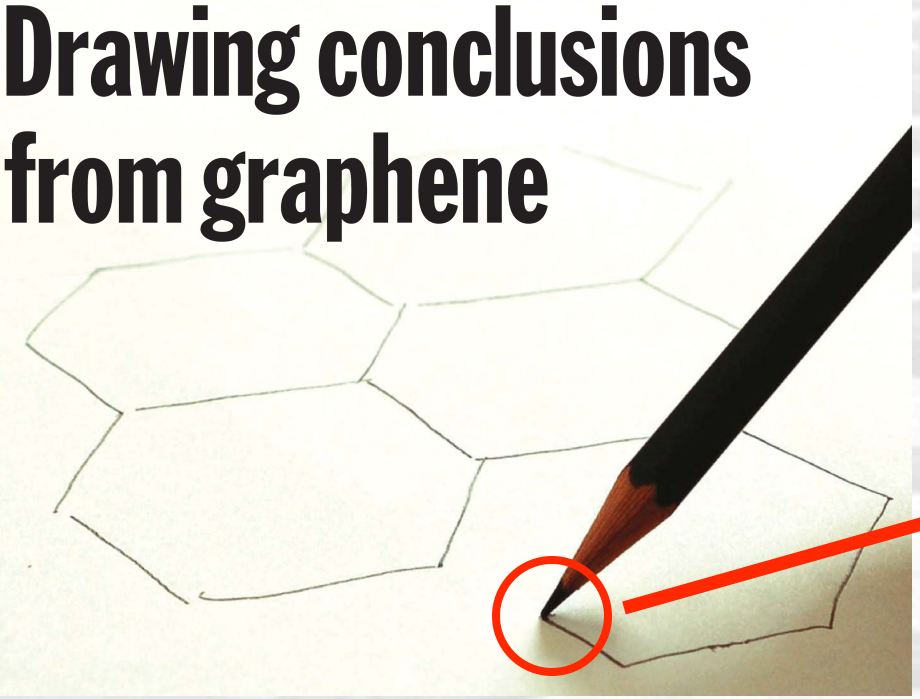




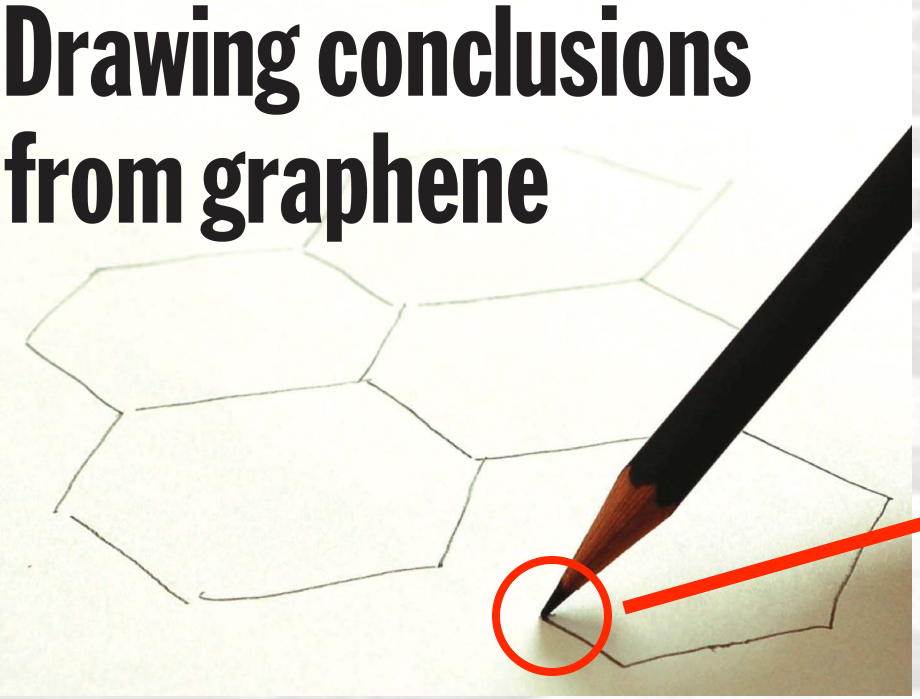
Drawing conclusions from graphene

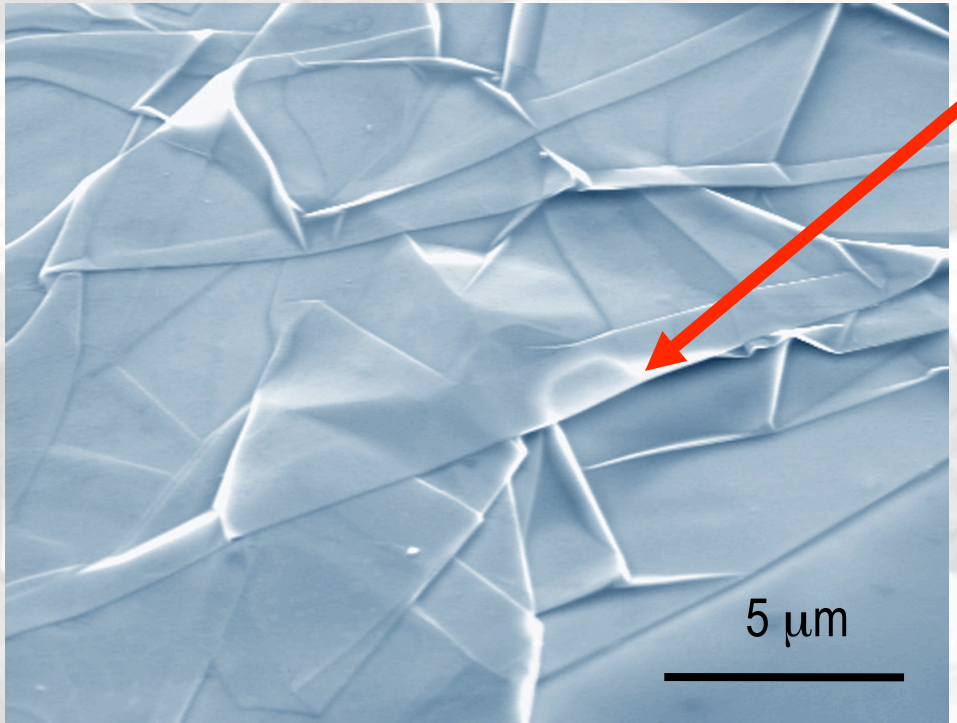


Drawing conclusions from graphene

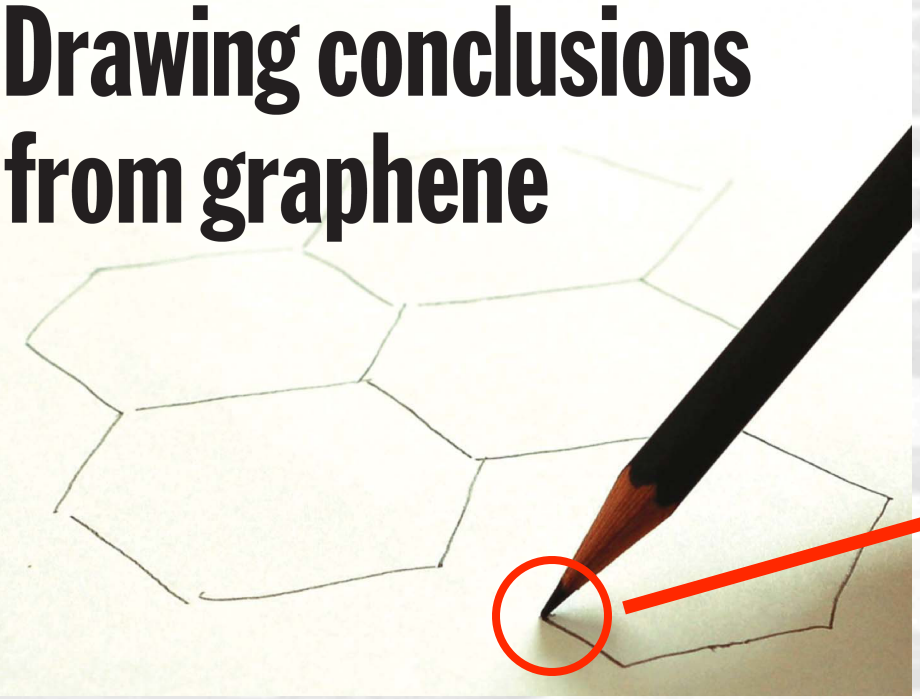


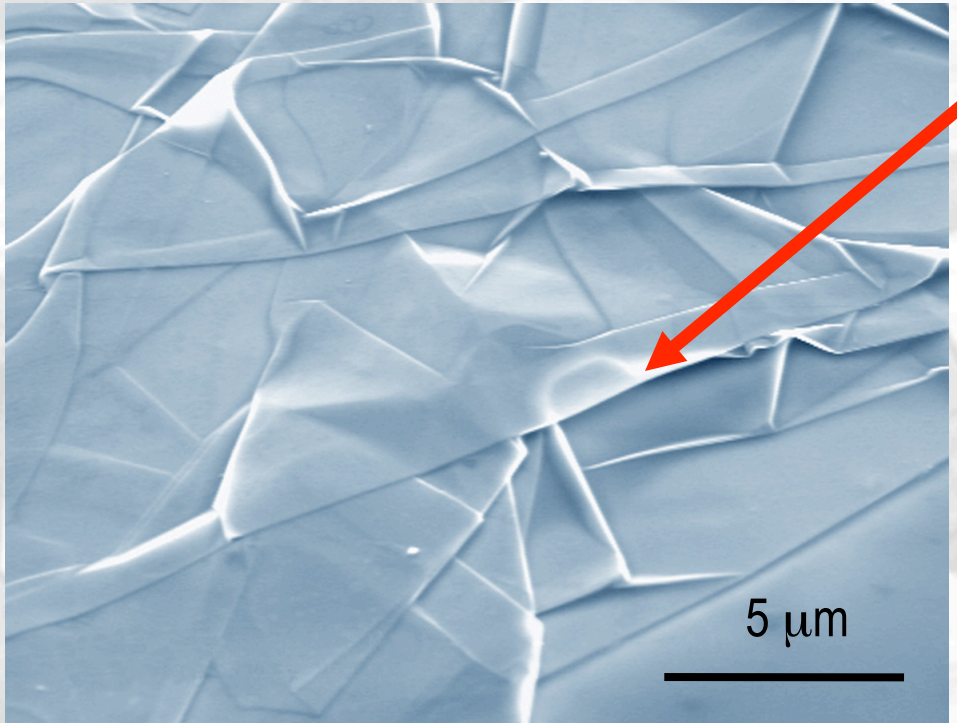
Drawing conclusions from graphene





Drawing conclusions from graphene





Graphene has been produced since the pencil was invented in England in 1564 !

From 1564 to 2004 !

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 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 insurmountable obstacle to metallic electronics, and no metal or semimetal has been shown to exhibit any notable (>1%) field effect (*4*).

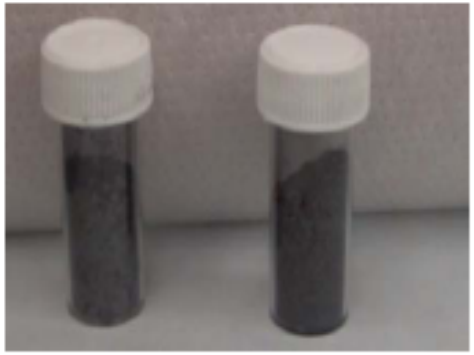
We report the observation of the electric field effect in a naturally occurring two-dimensional (2D) material referred to as few-layer graphene (FLG). Graphene is the name given to a single layer of carbon atoms densely packed into a benzene-ring structure, and is widely used to describe properties of 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*).

[1]Department of Physics, University of Manchester, Manchester M13 9PL, UK. [2]Institute for Microelectronics Technology, 142432 Chernogolovka, Russia.

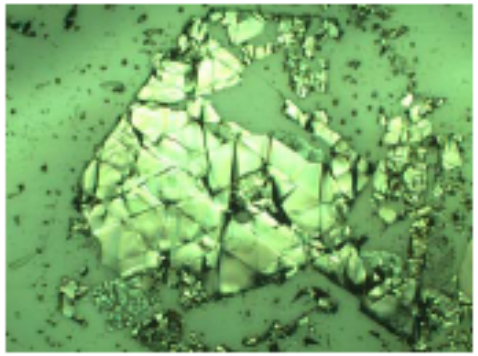
*To whom correspondence should be addressed. E-mail: geim@man.ac.uk

Recipe for making a graphene transistor

Recipe for making a graphene transistor

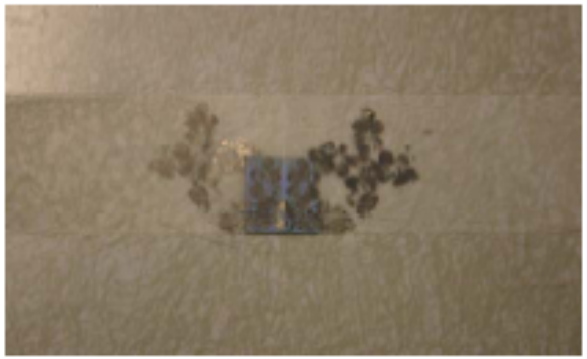


Graphite Flakes (Kish, Toshiba Ceramics)



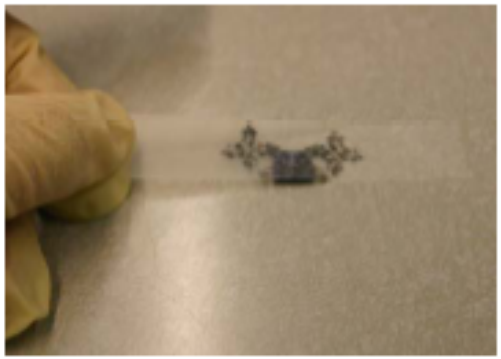
Graphite Flake

Peeling a Graphite Flake

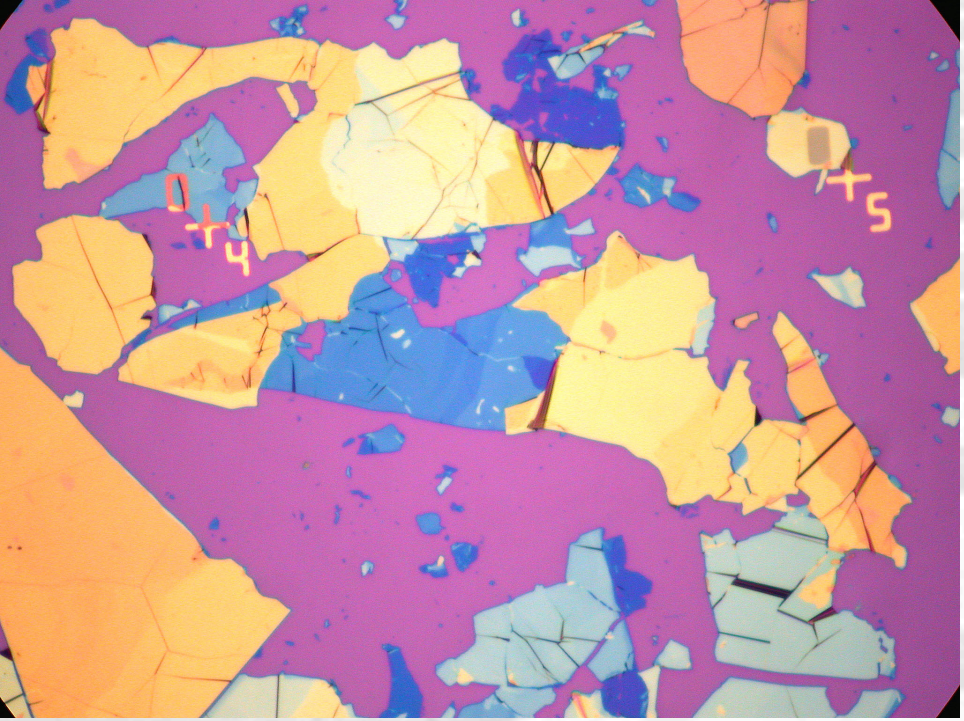


Cleaving to a SiO_2/Si waver

Gentle Rubbing with plastic Tweezers



Removing the Scotch Tape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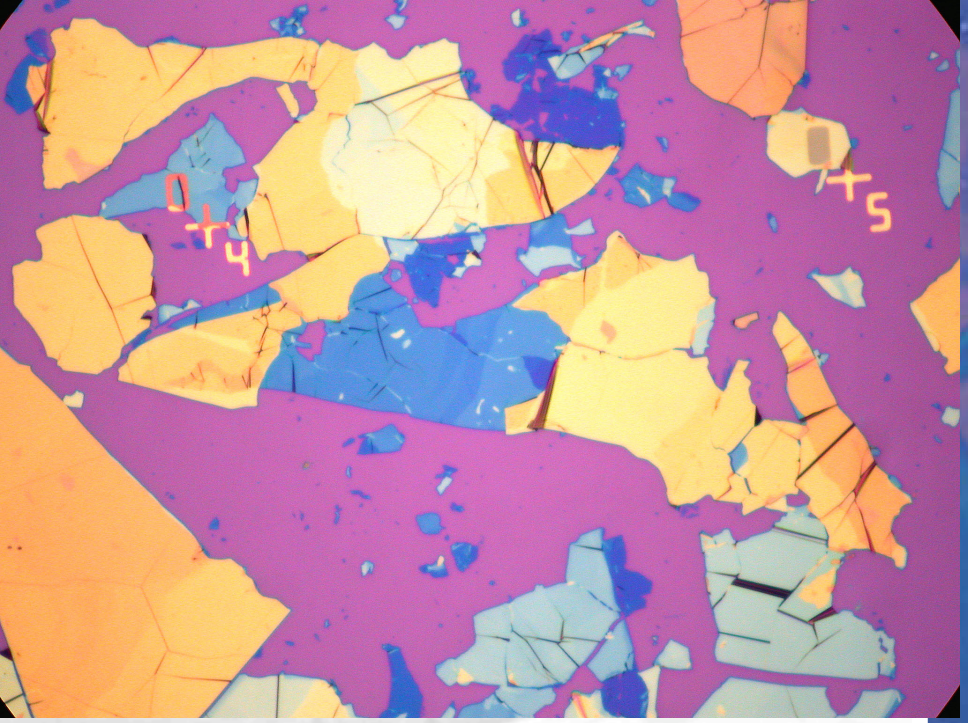
0+5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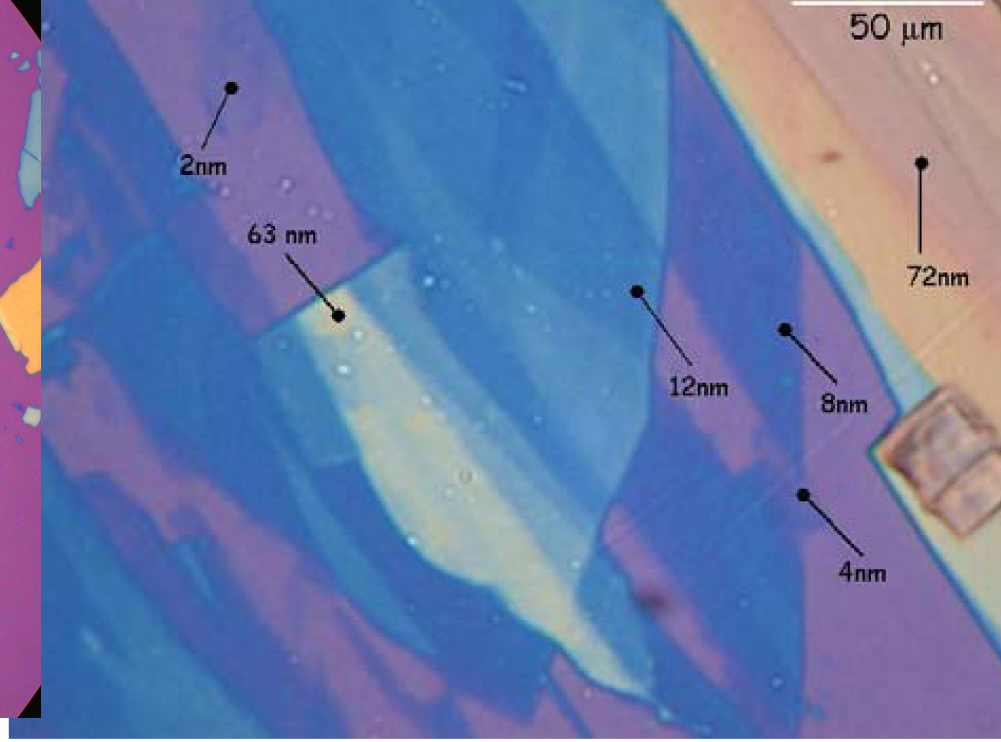
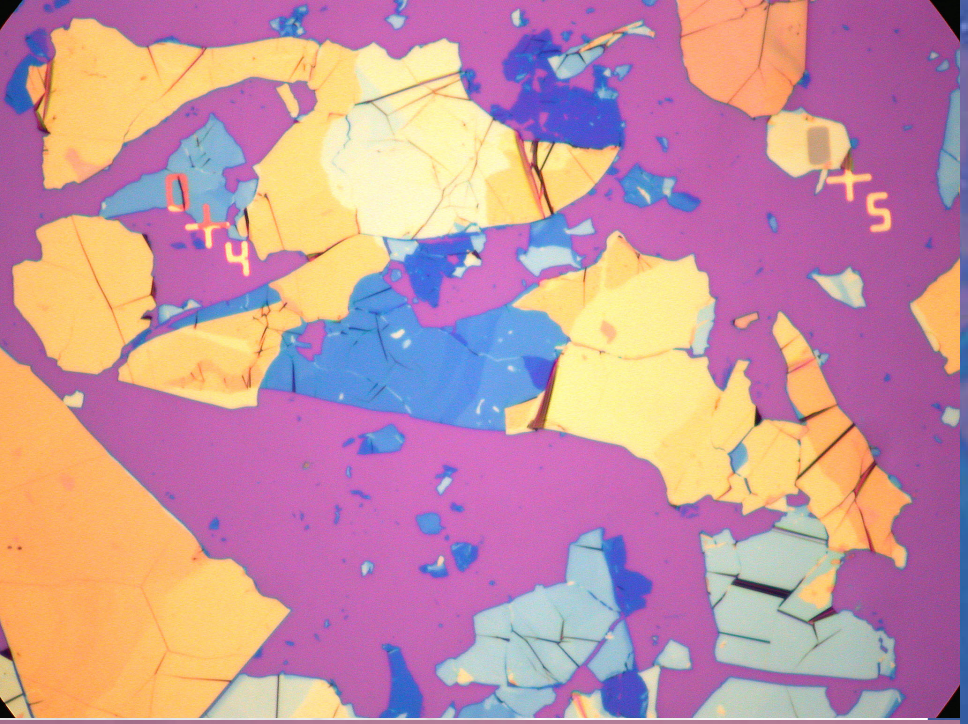

50 µm
2nm
63 nm
72nm
12nm
8nm
4nm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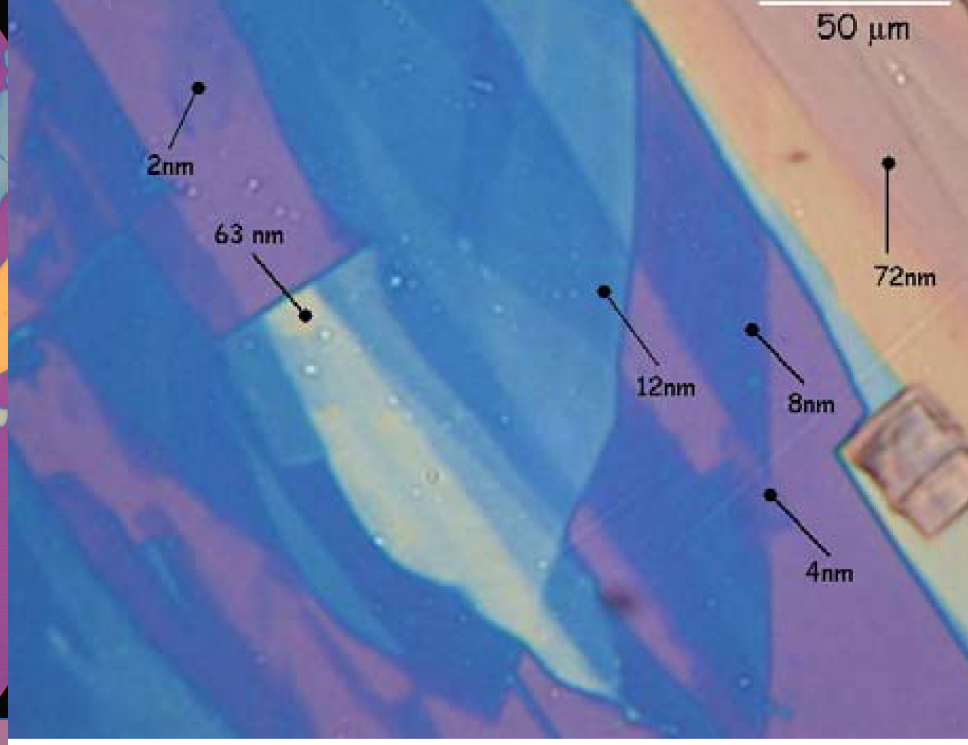
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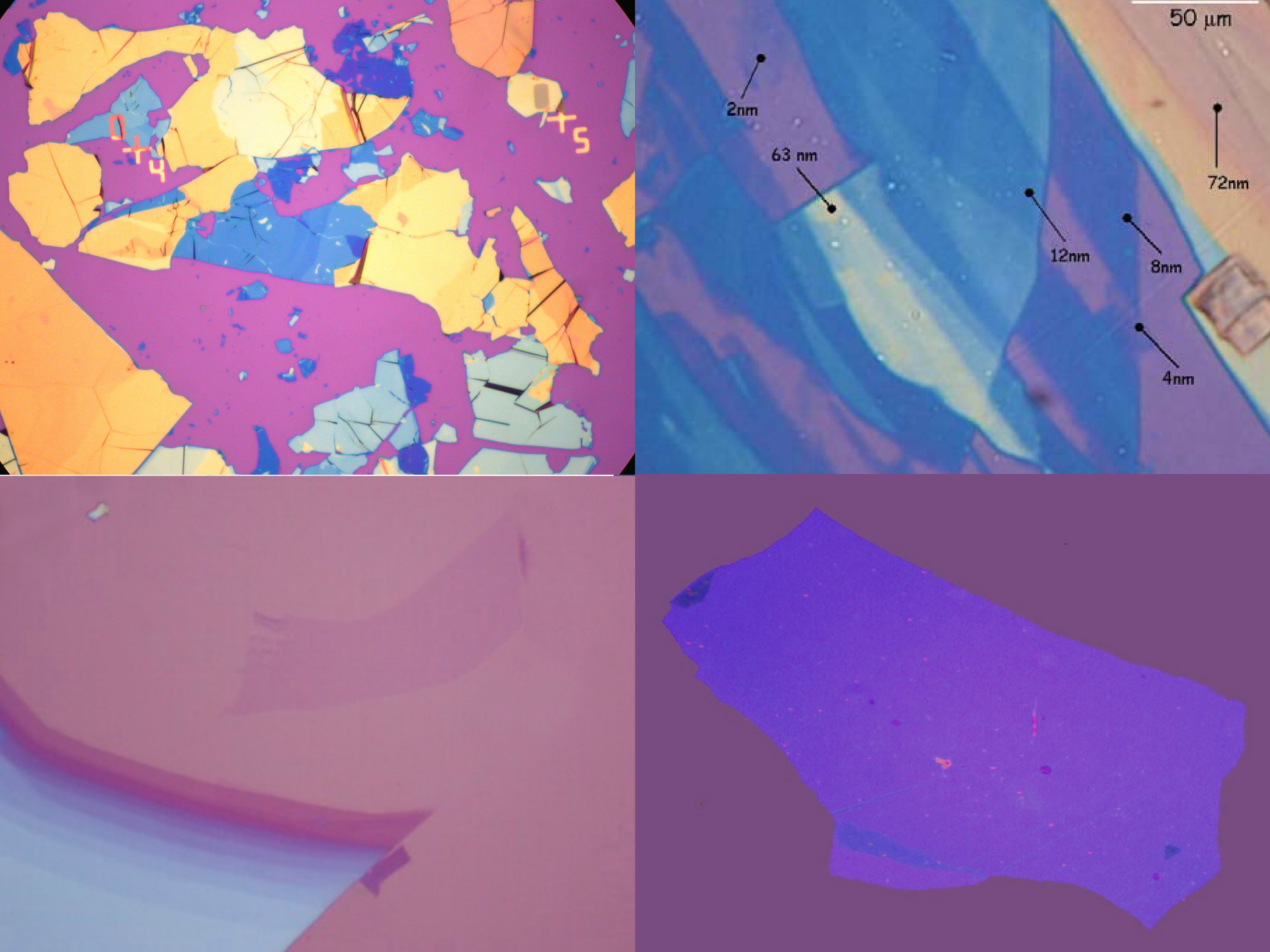
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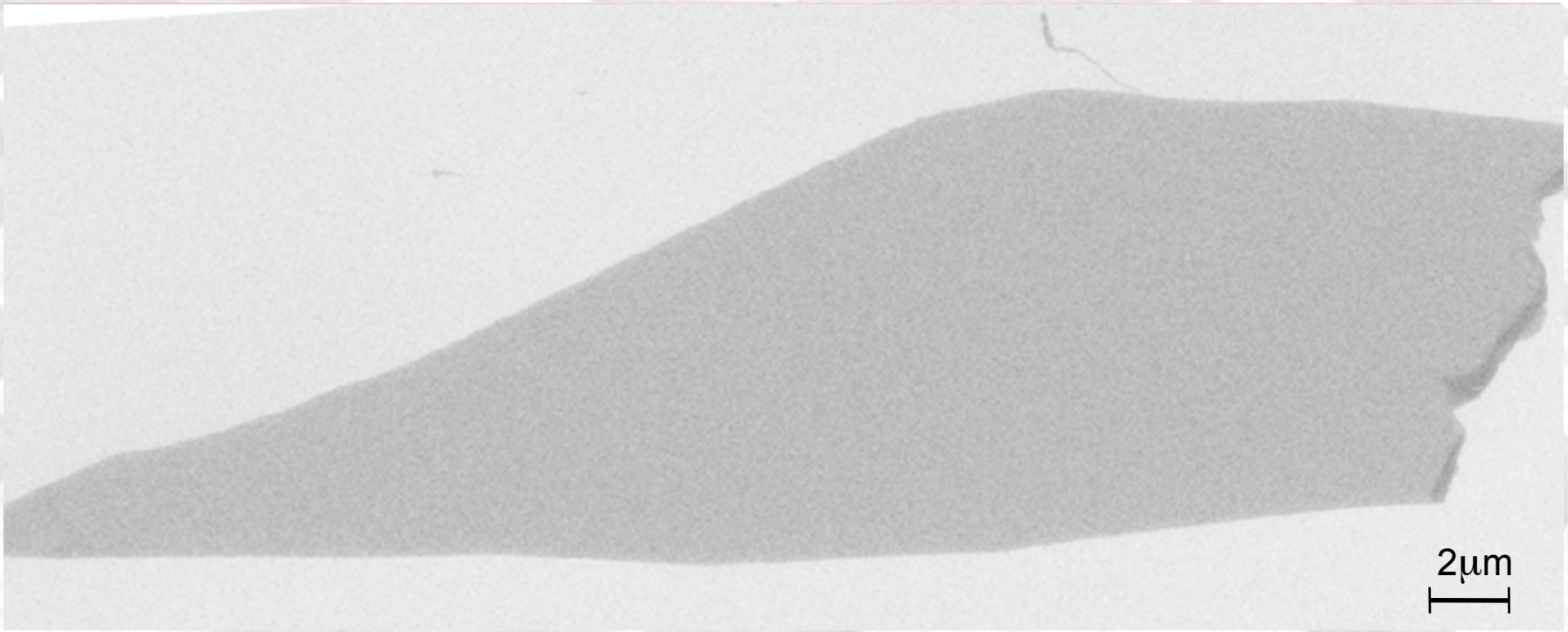
Plus some nanotechnology…

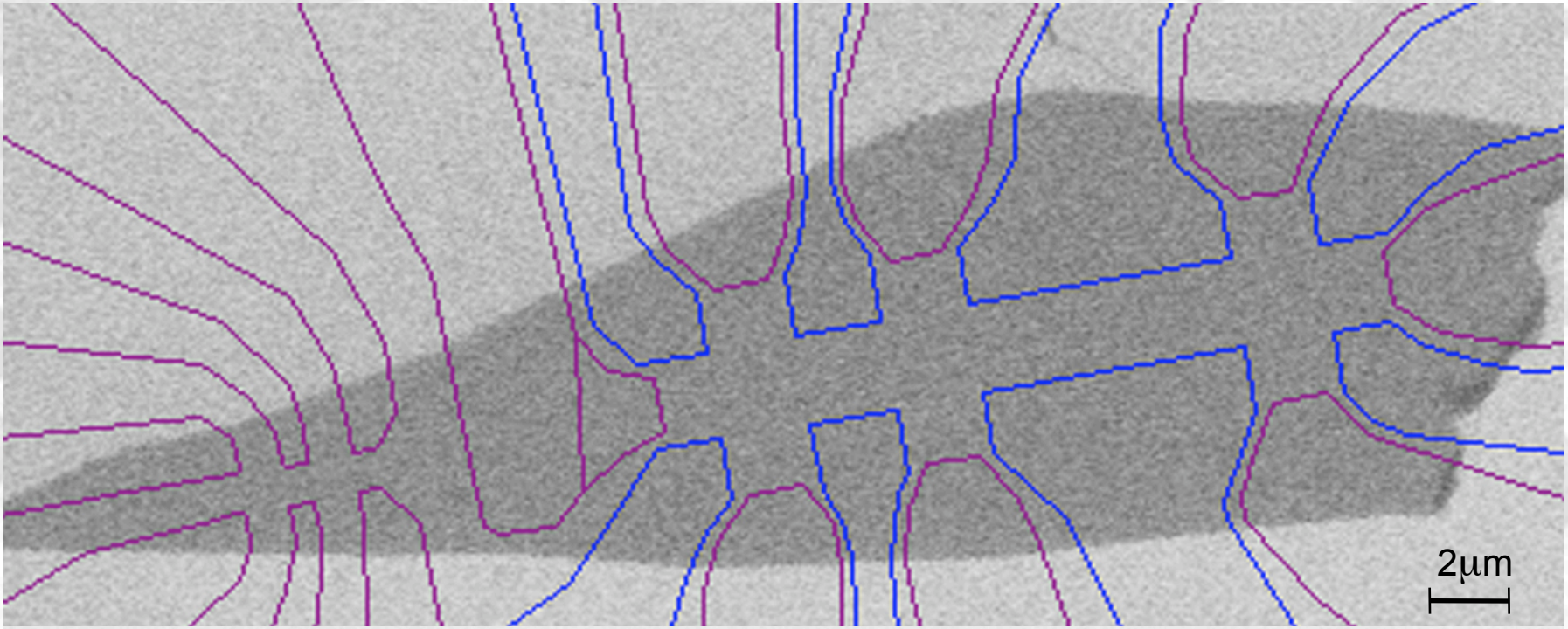
- optical image

Plus some nanotechnology…



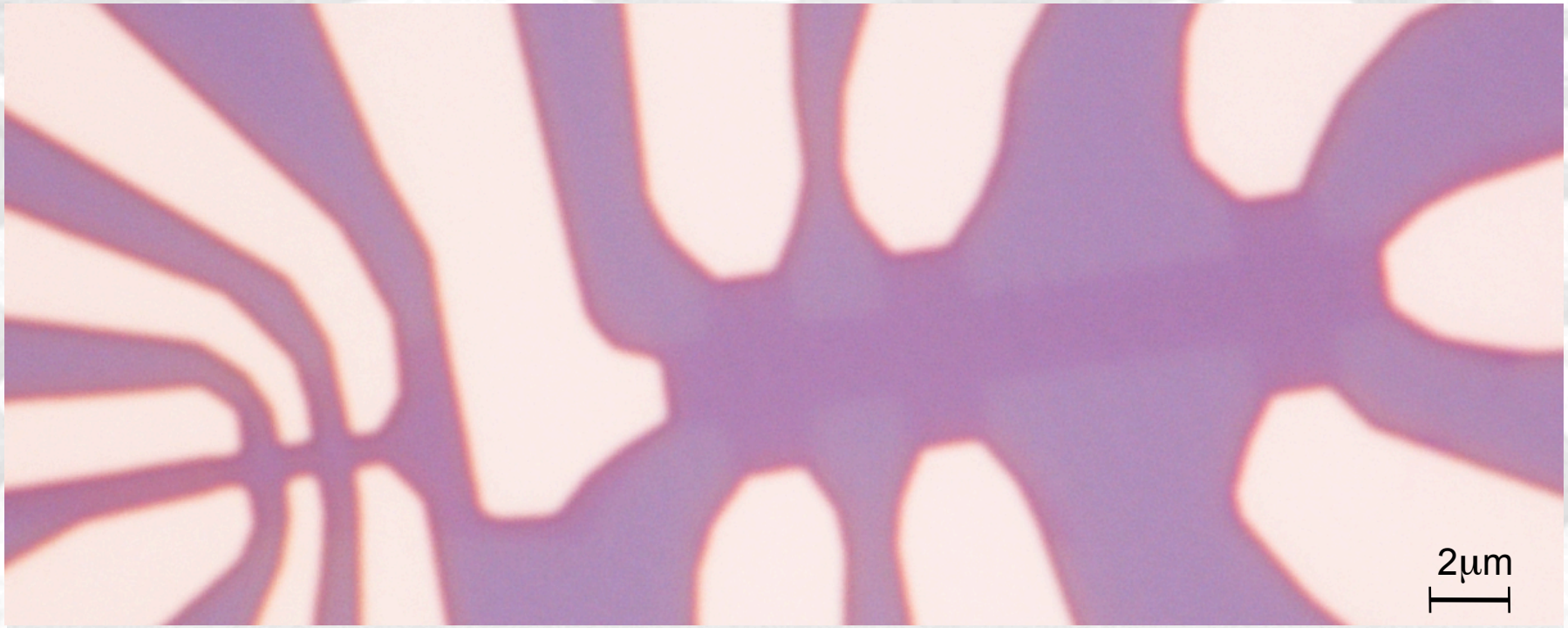
- optical image
- SEM image

Plus some nanotechnology…

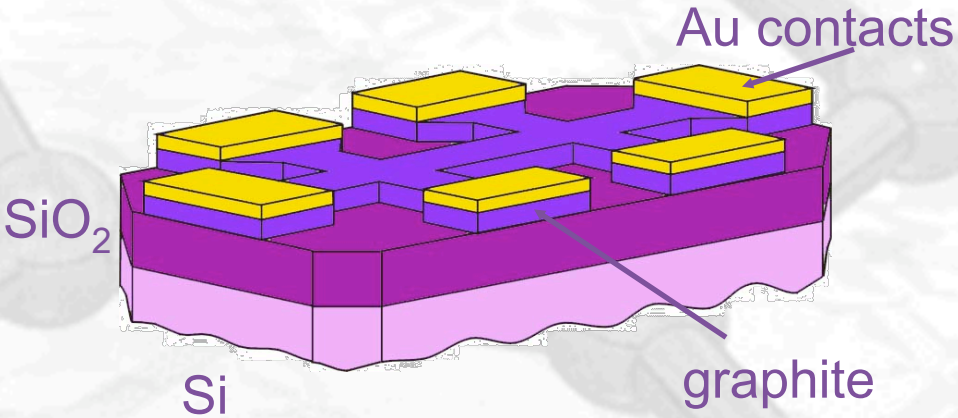


- optical image
- SEM image
- design

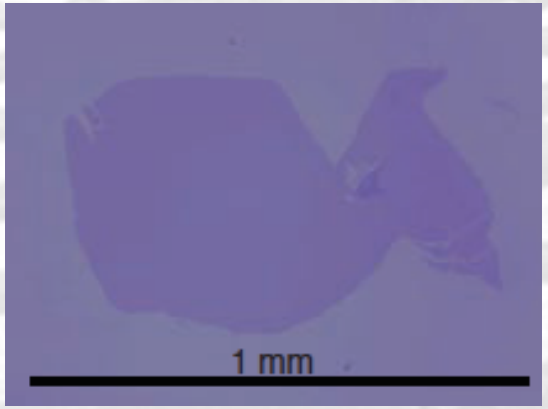
Plus some nanotechnology…



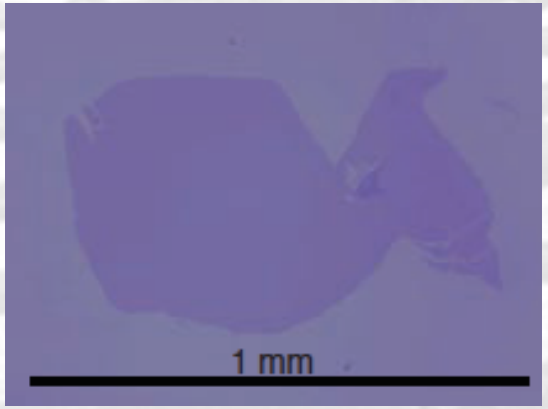
- optical image
- SEM image
- design
- contacts and mesa



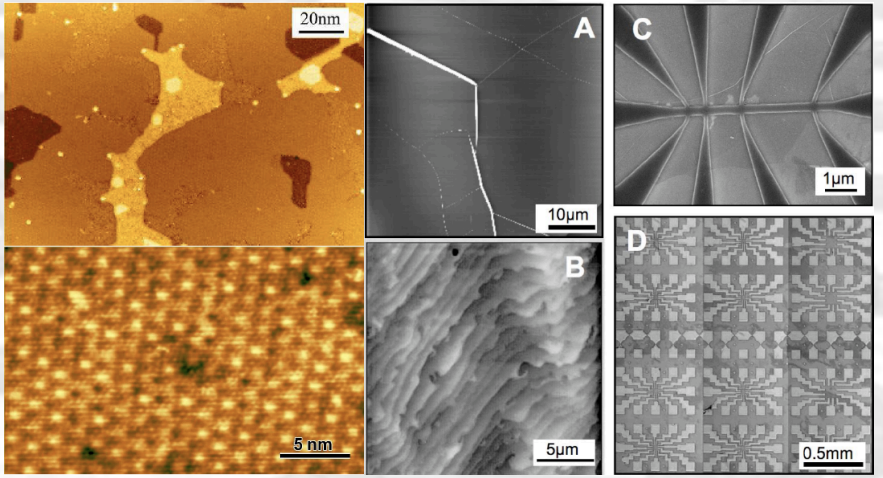
Exfoliation



Exfoliation

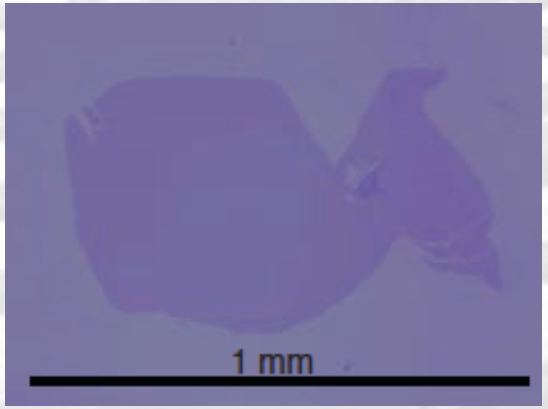


Growth on SiC



Berger et al., J. Phys. Chem. B, 2004, 108 (52)

Exfoliation



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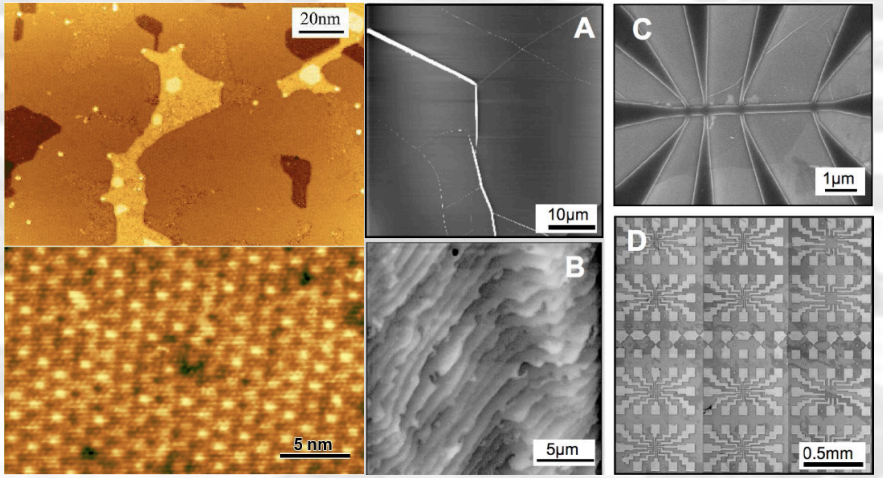

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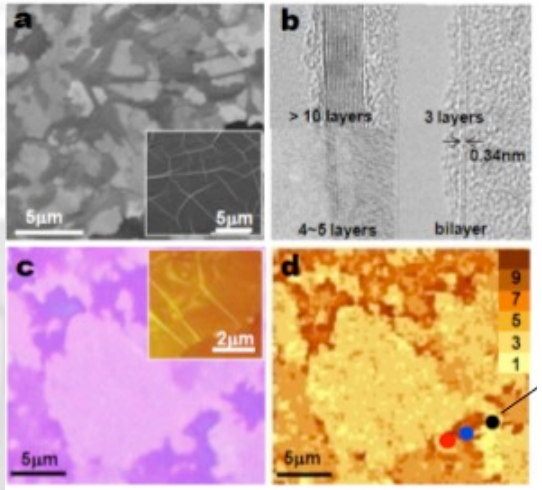
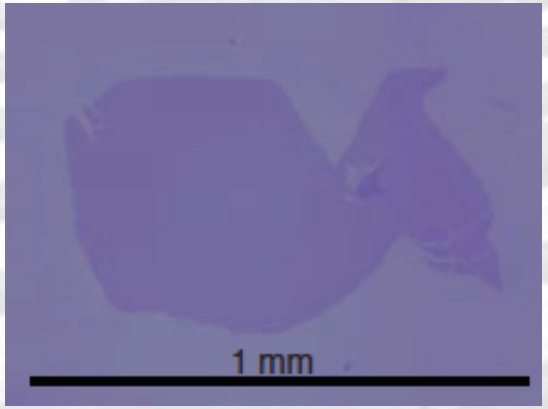
Growth by CVD



Kim et al., Nature **457**, 706-710 (2009)

Exfoliation



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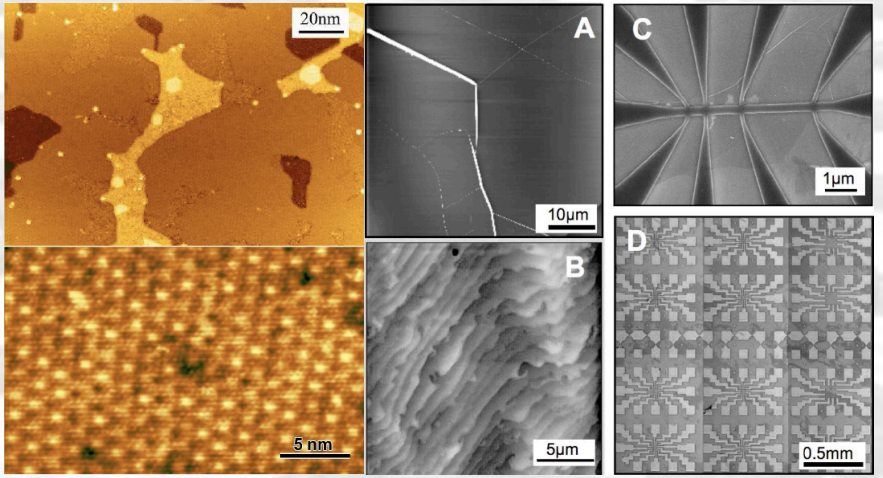

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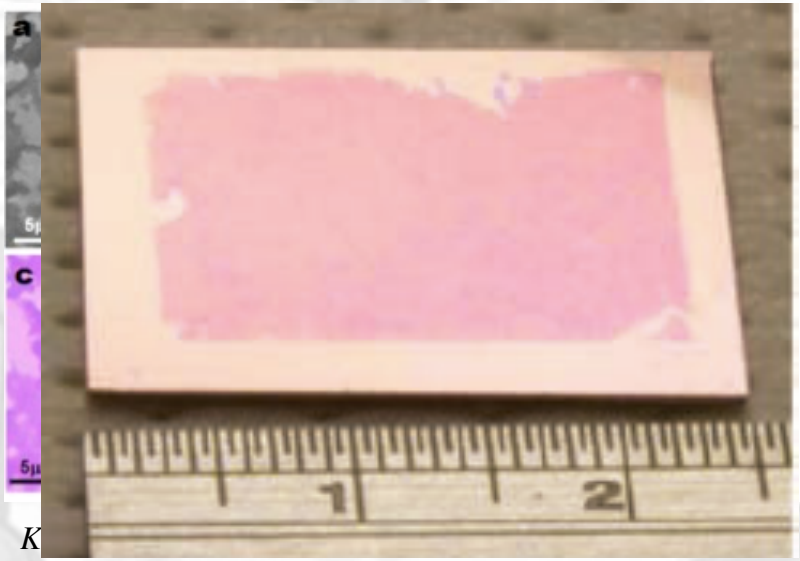
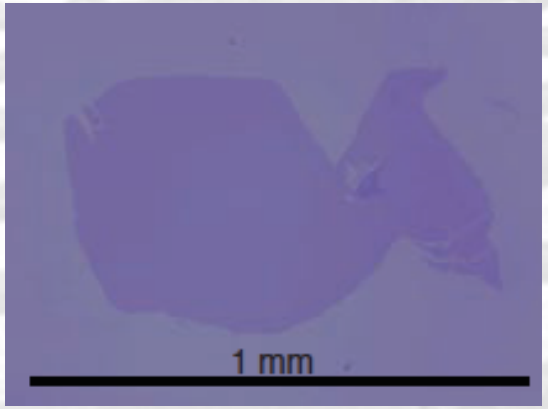


Exfoliation



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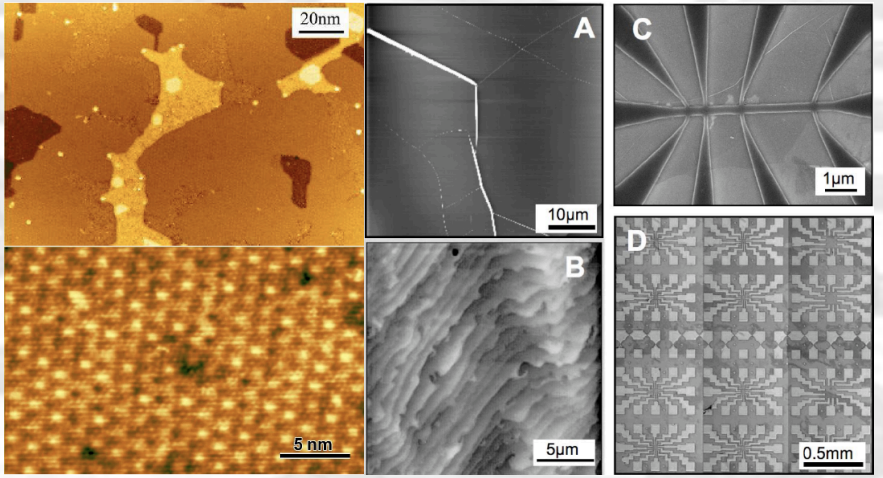

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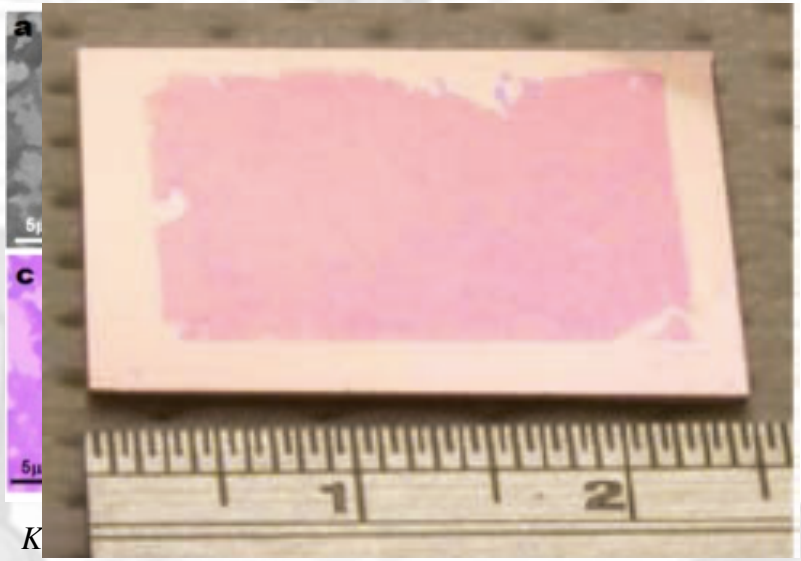

What is so special about graphene ?

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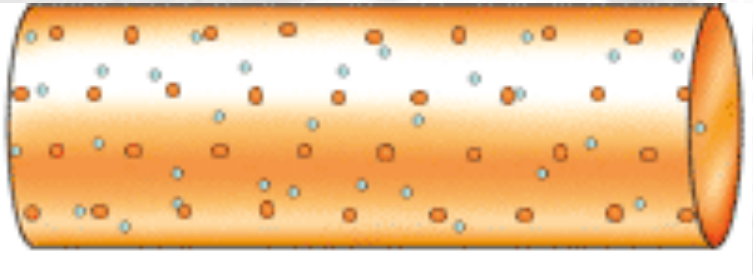
Normal conductor



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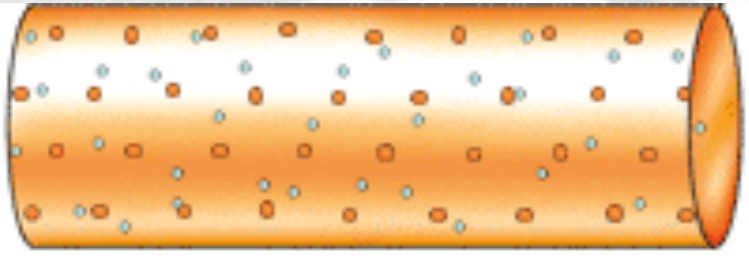
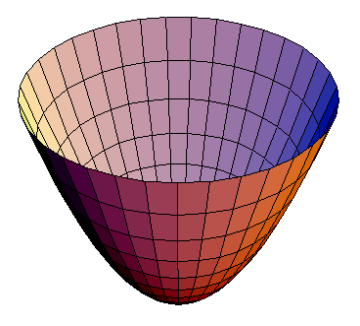


Fermions

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



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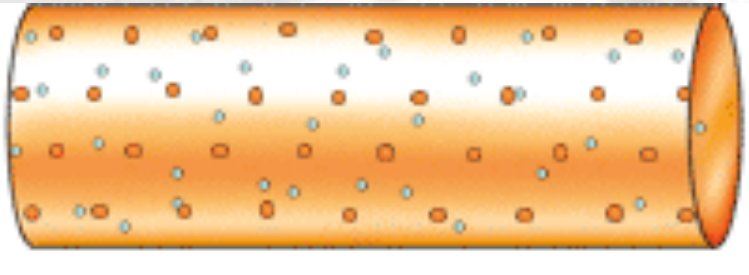

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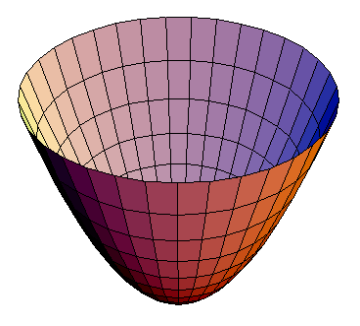
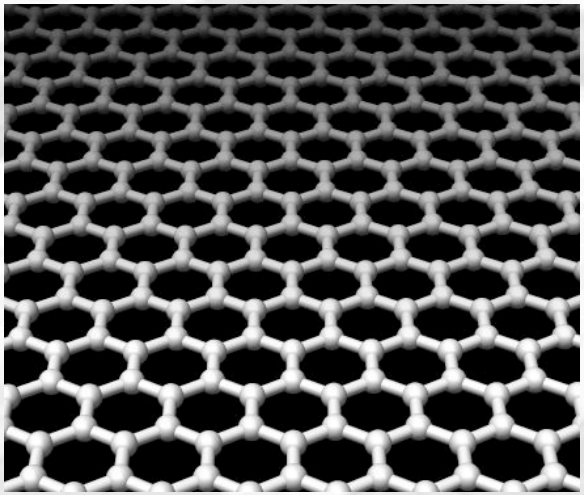


Graphene



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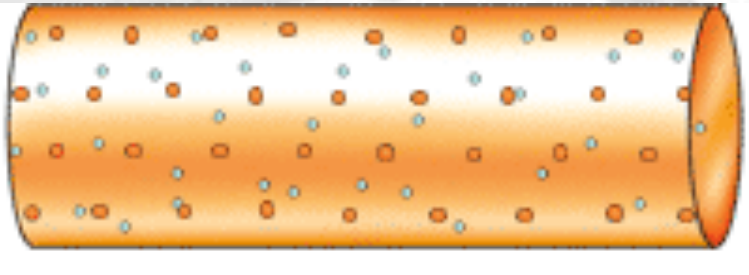

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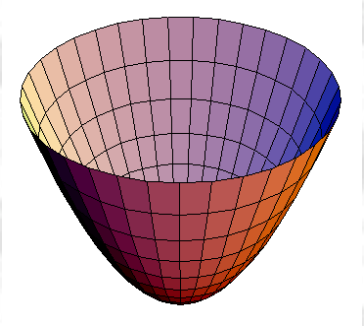

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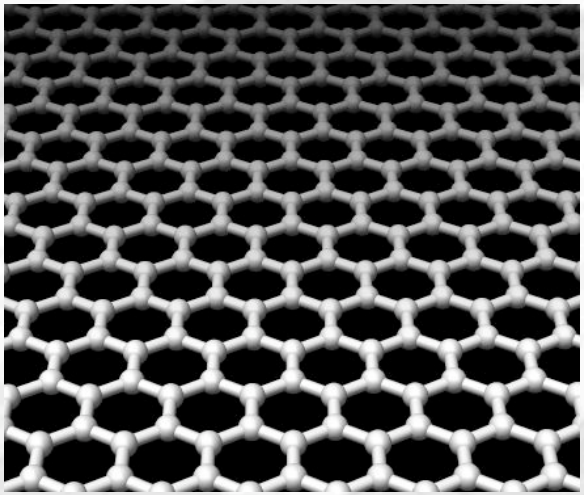
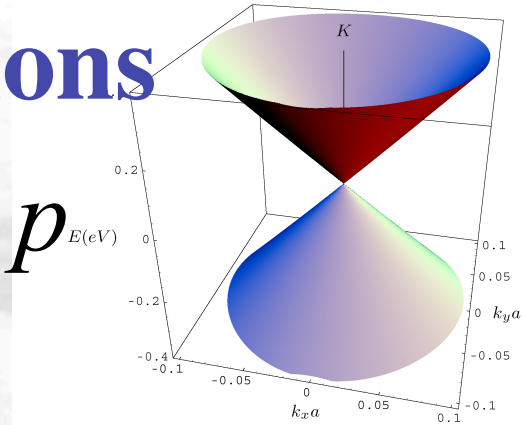


Dirac fermions

$$E(p) = \pm v\, p$$



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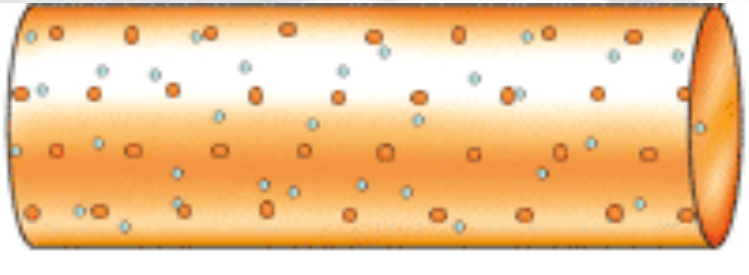

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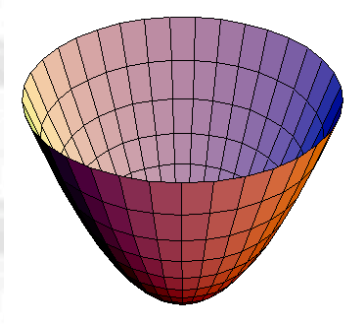
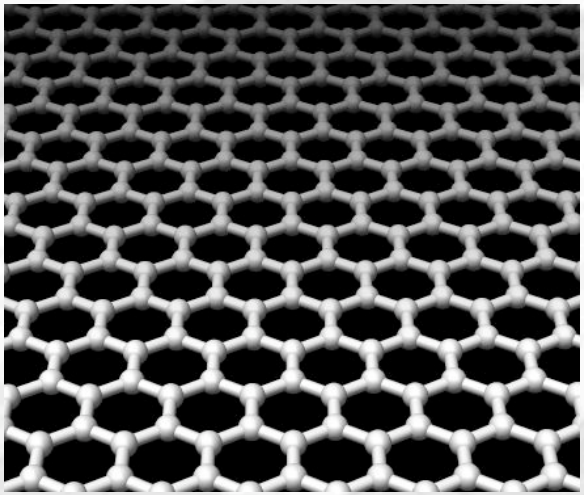


Graphene



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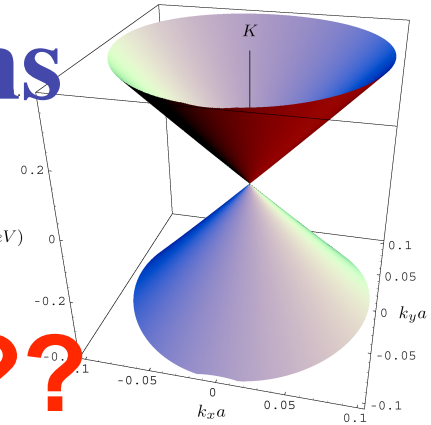

But how ???

REVIEWS OF MODERN PHYSICS, VOLUME 81, JANUARY–MARCH 2009

The electronic properties of graphene

A. H. Castro Neto

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(Published 14 January 2009)

Paco Guinea

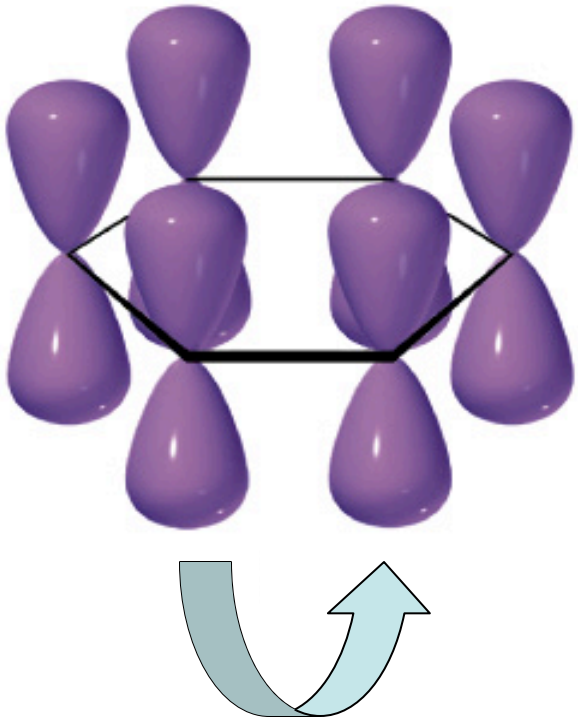
Nuno Peres

Kostya Novoselov

Andre Geim

Benzene molecule

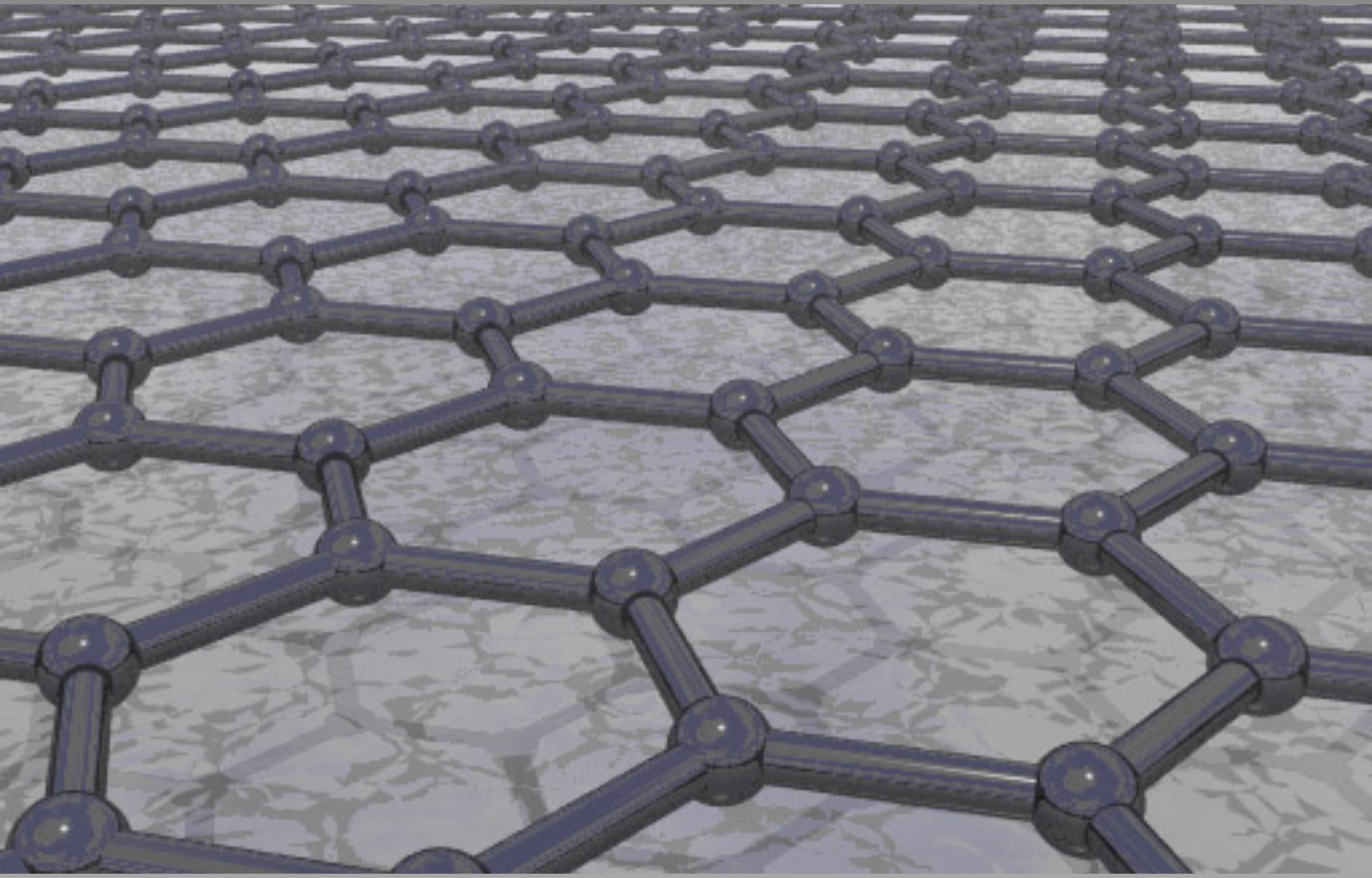
p_z states



π state

t ~ 2.7 eV

Origin of Dirac fermions in graphene



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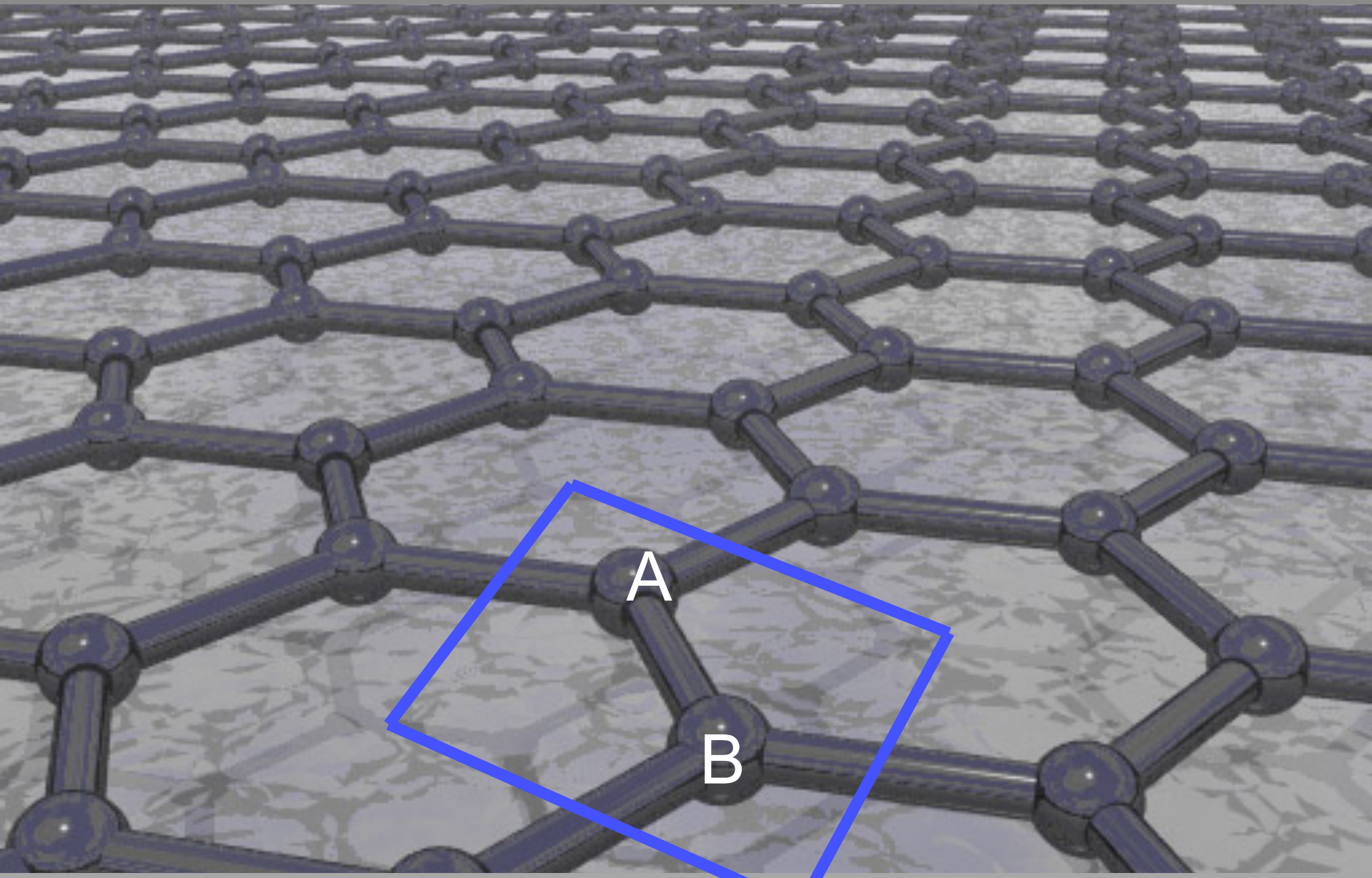
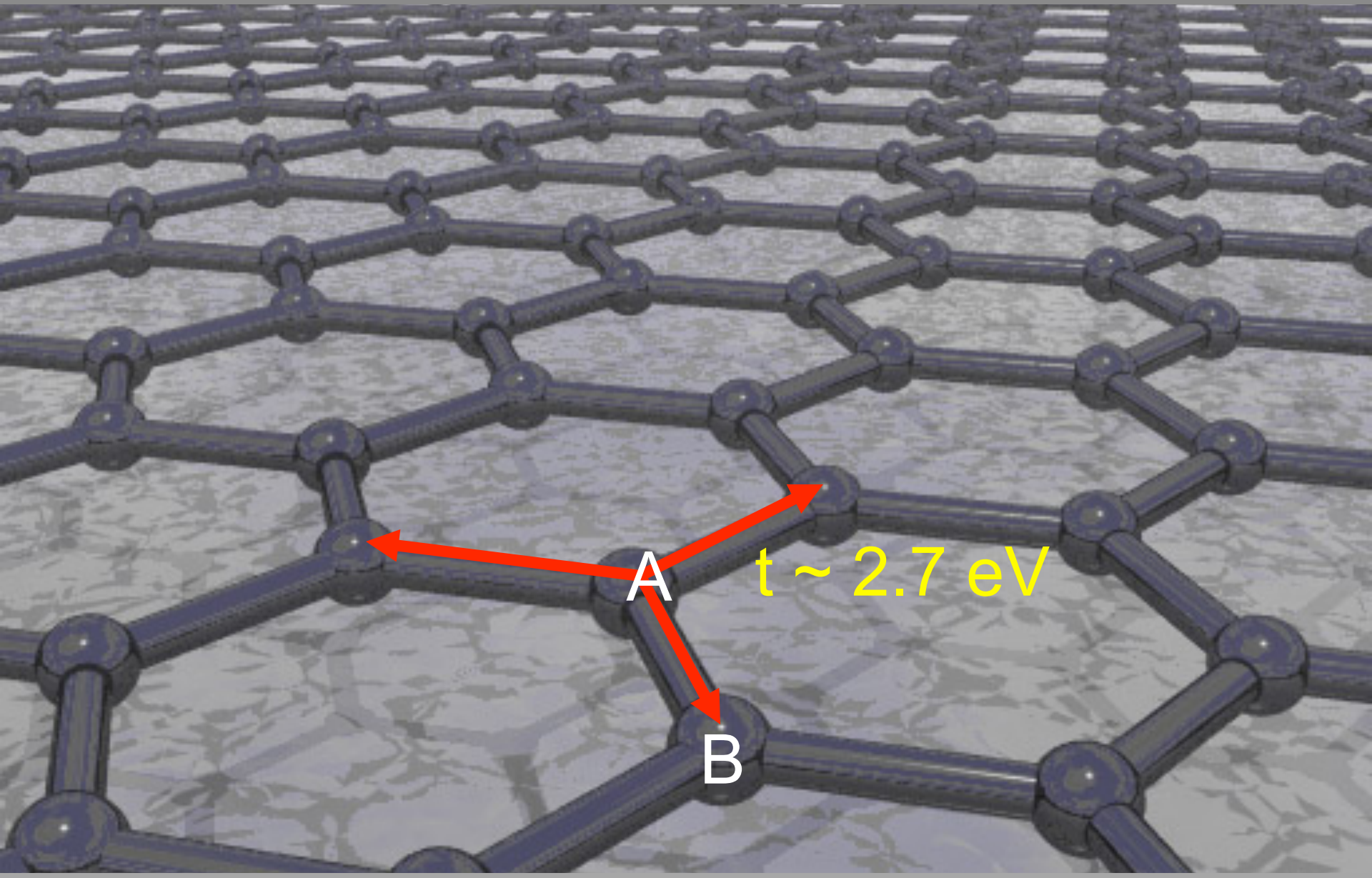


Unit cell

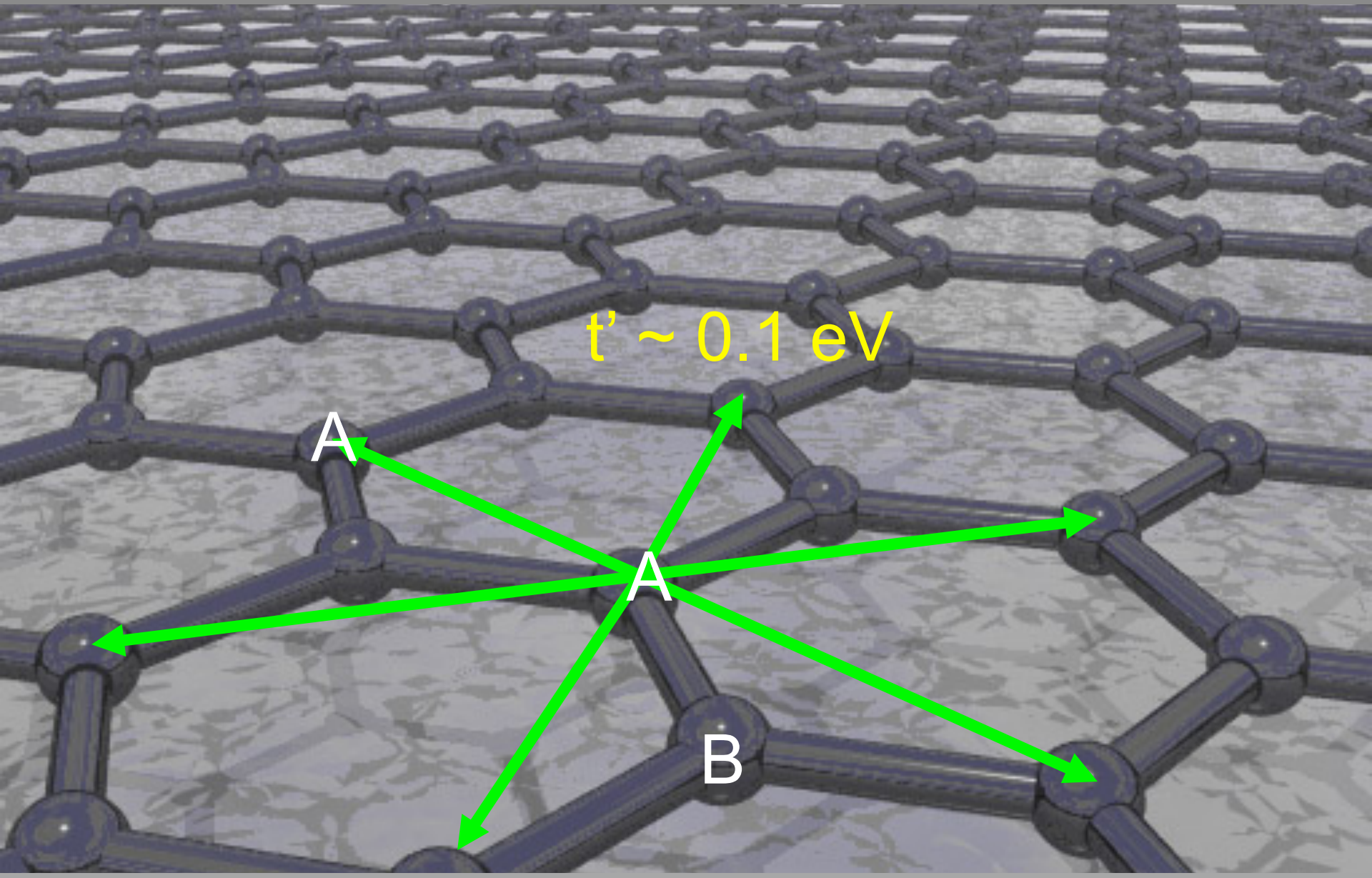
Origin of Dirac fermions in graphene



Unit cell

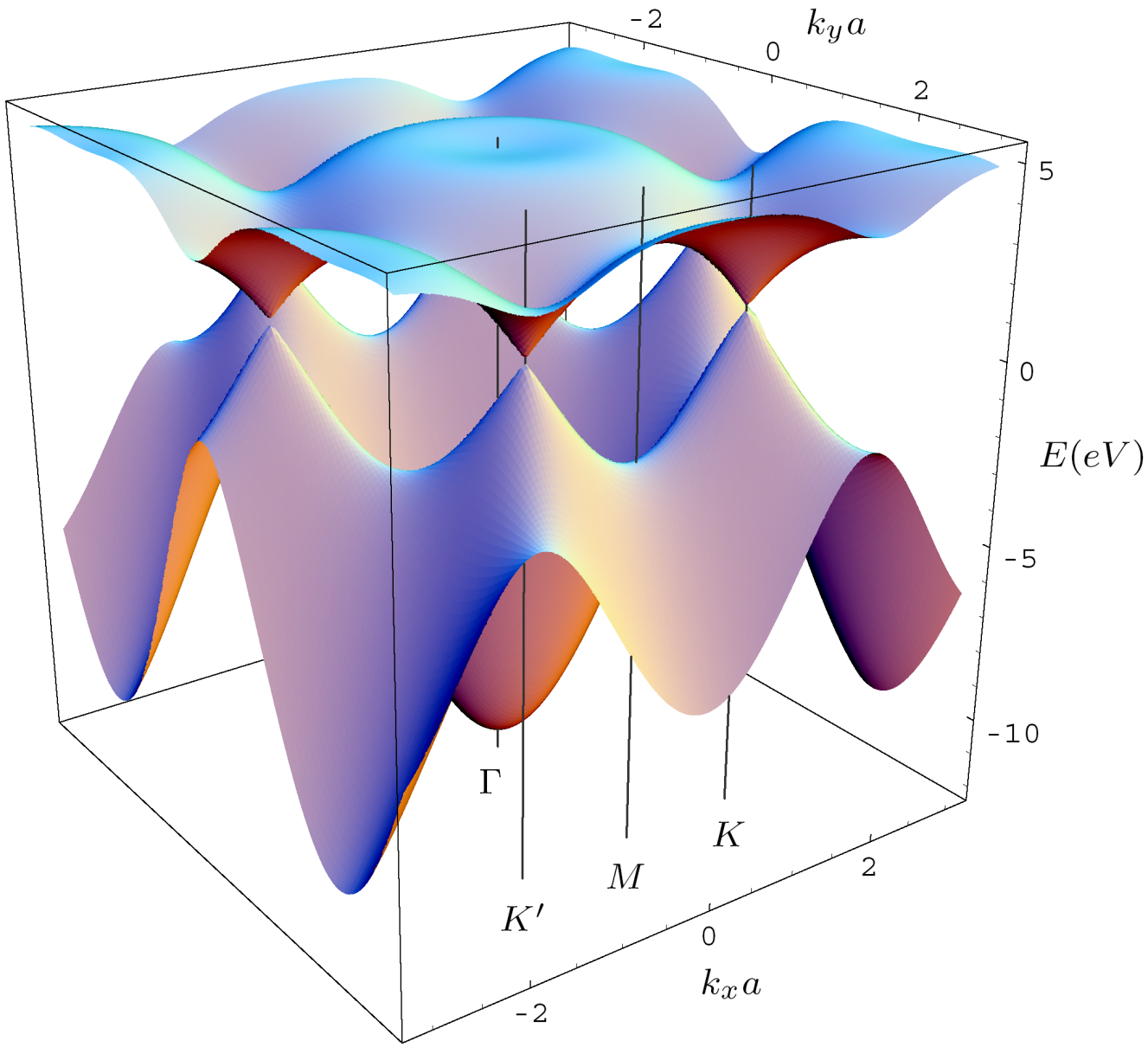
Nearest neighbors

Origin of Dirac fermions in graphene

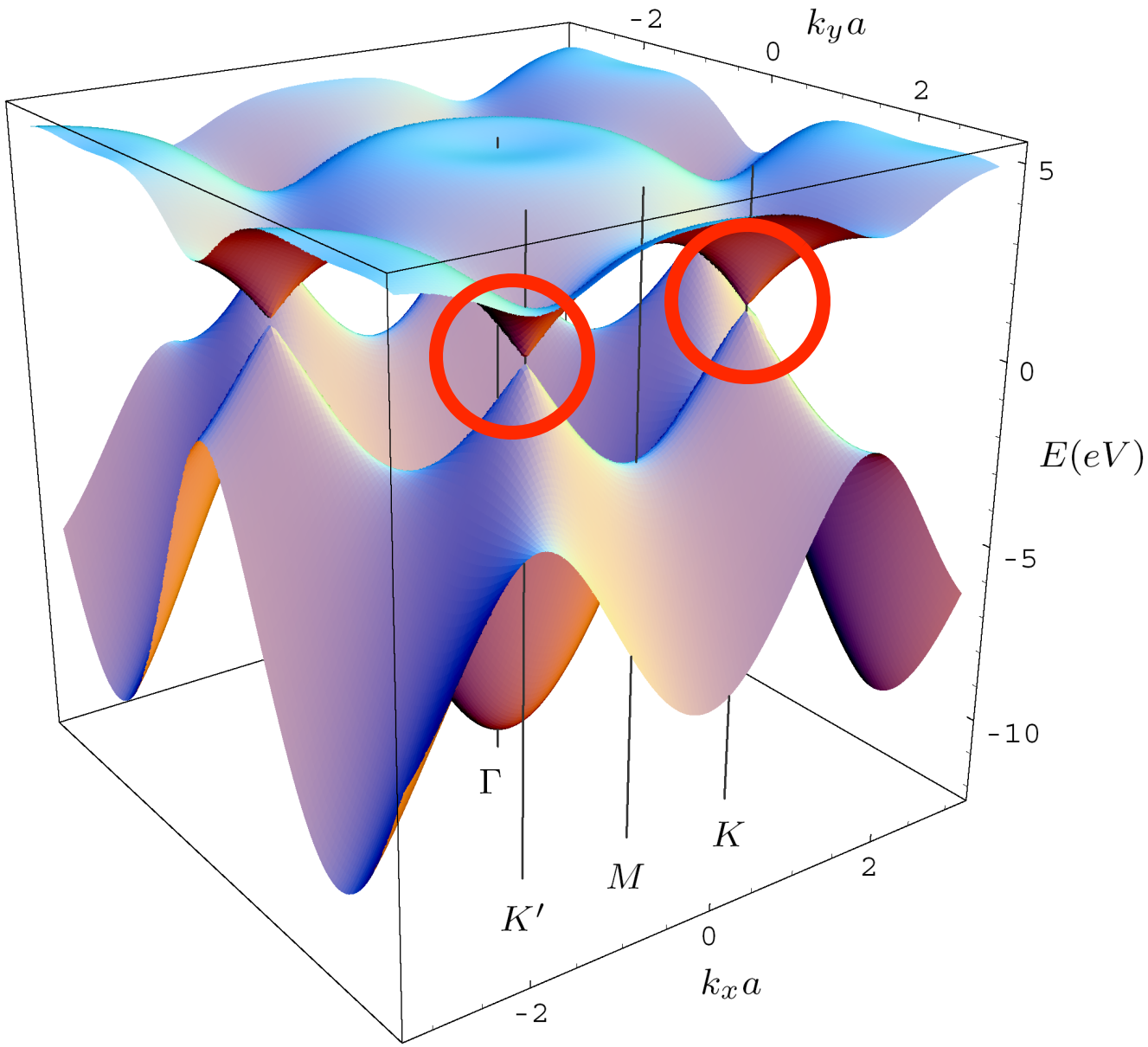


Next Nearest neighbors

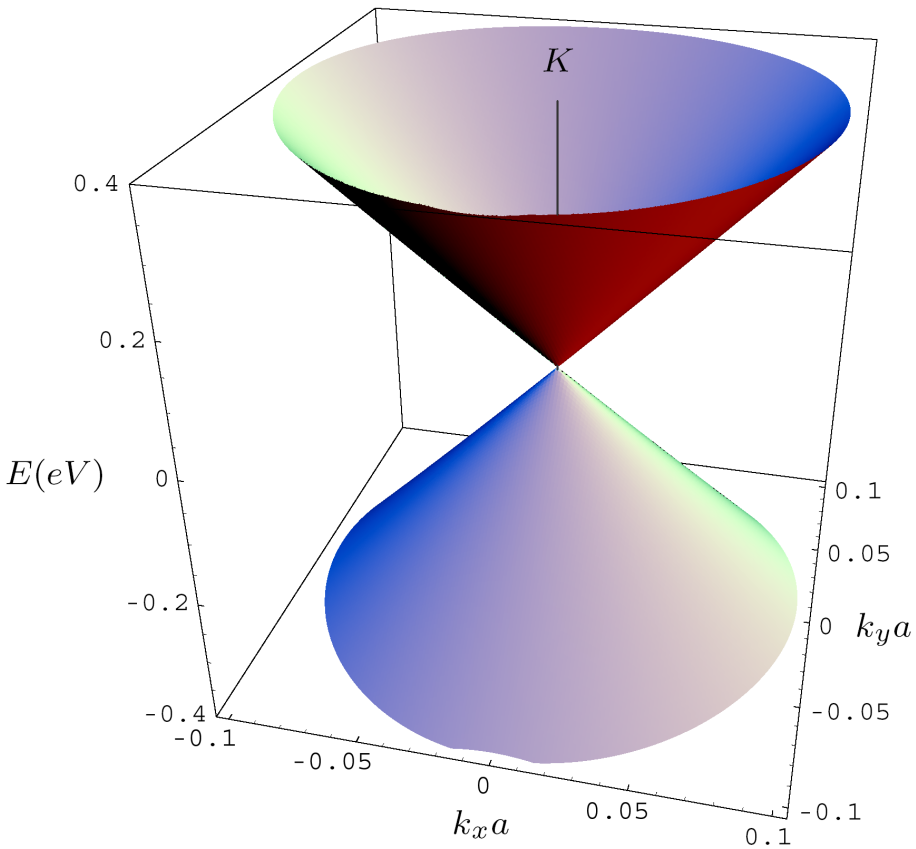
In momentum space



In momentum space

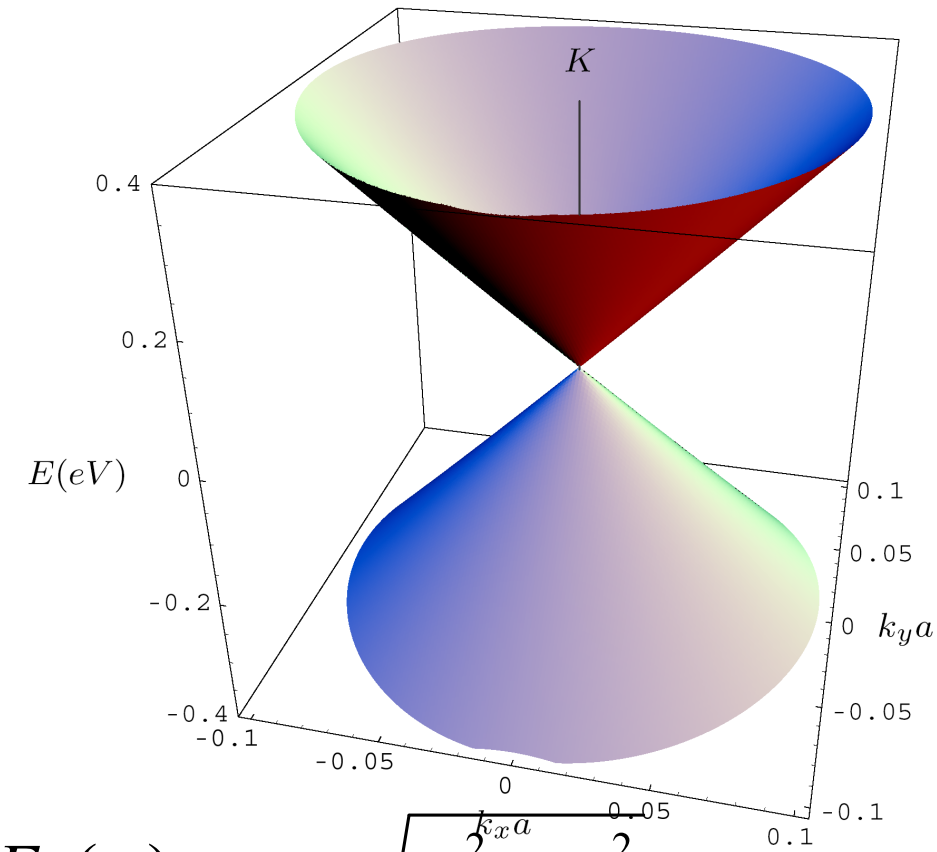


In momentum space



Dirac Cone

In momentum space



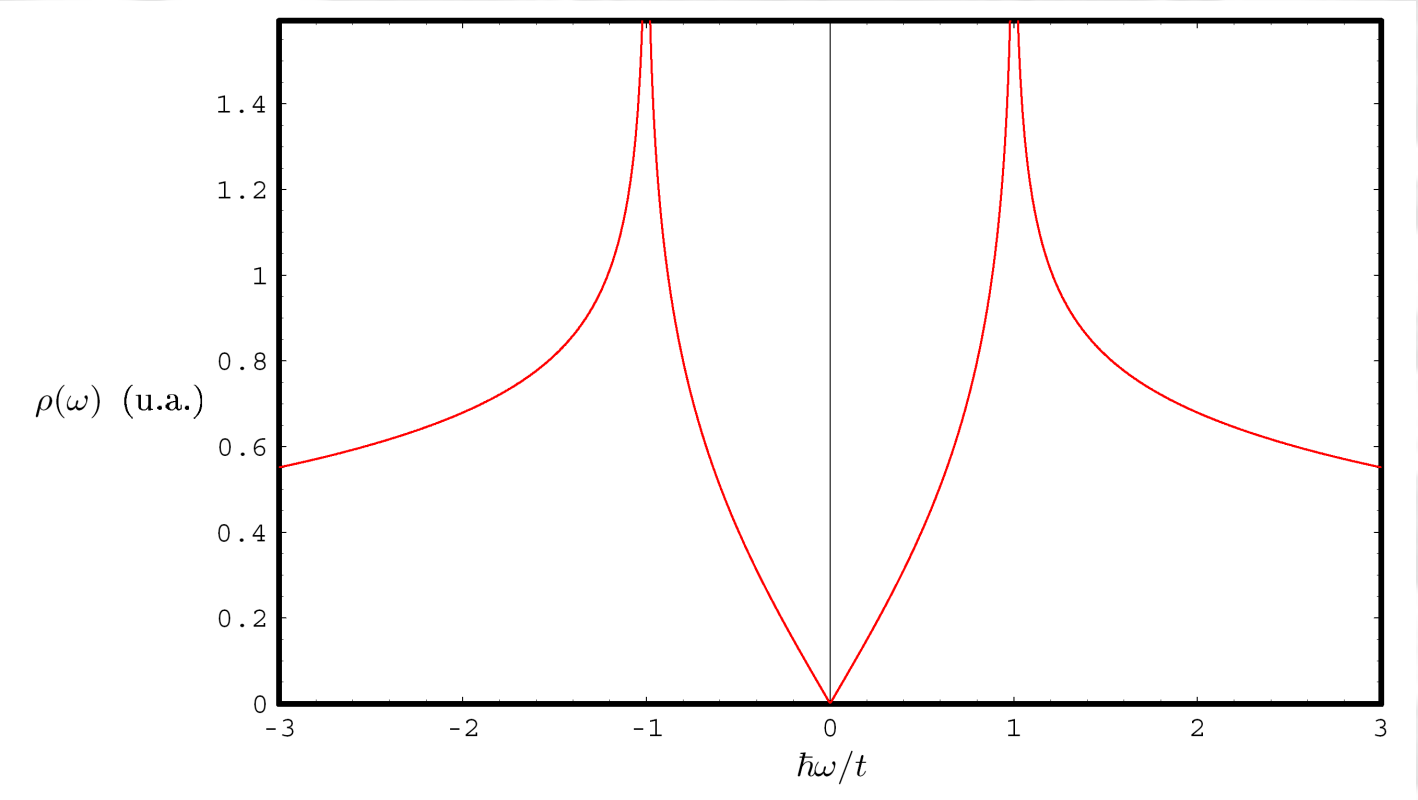
Dirac Cone

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

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

$$v_F = \frac{3ta}{2} \approx c/300$$

In momentum space



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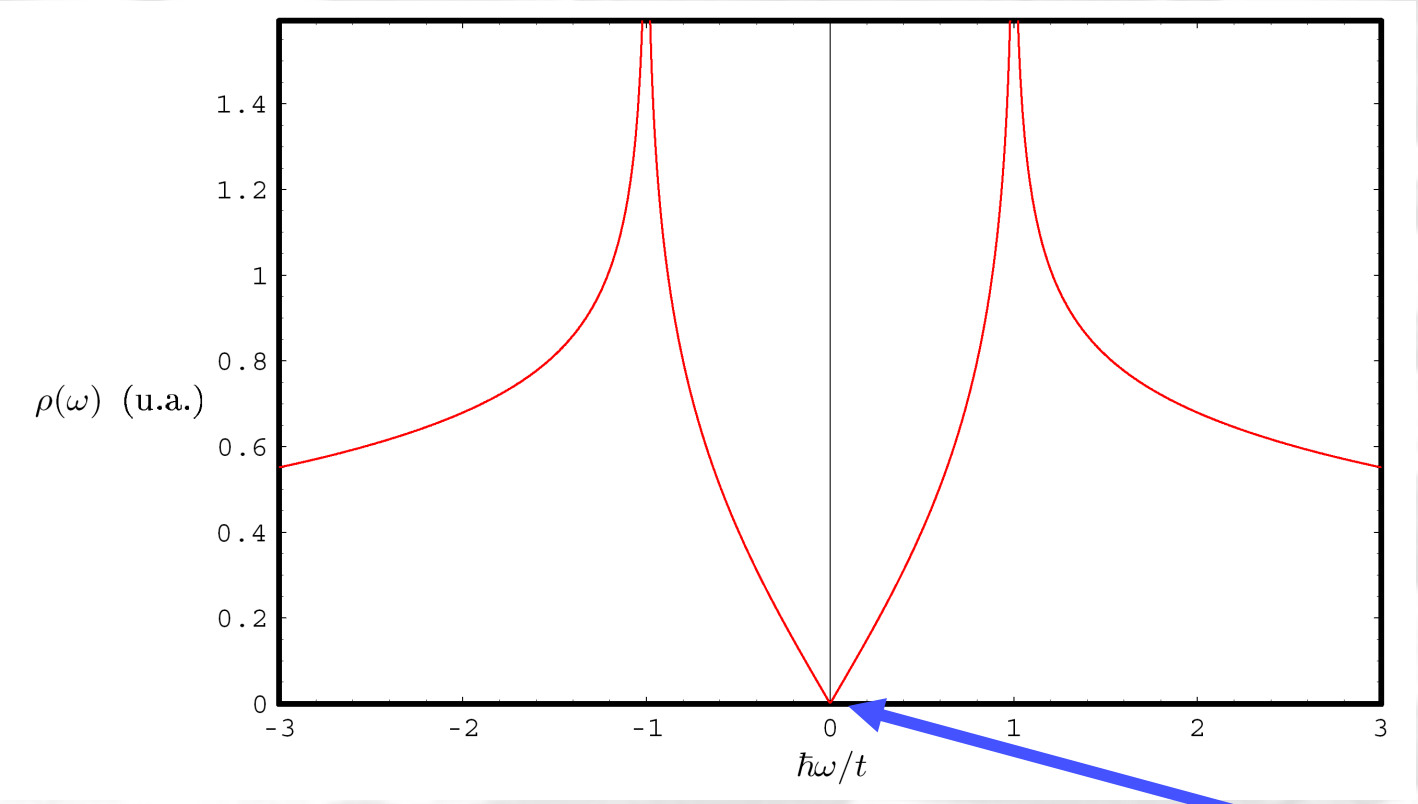

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$$v_F = \frac{3ta}{2} \approx c/300$$

Vanishing density of states

Mathematically

$$H = v_F \begin{bmatrix} 0 & p_x - ip_y \\ p_x + ip_y & 0 \end{bmatrix}$$

$$H\Psi_\pm(\mathbf{p}) = \pm v_F p \Psi_\pm(\mathbf{p})$$

$$\sigma \cdot \mathbf{u_p} \Psi_\pm(\mathbf{p}) = \pm \Psi_\pm(\mathbf{p})$$

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Chirality (helicity)

+ = right handed; - = left handed

Mathematically

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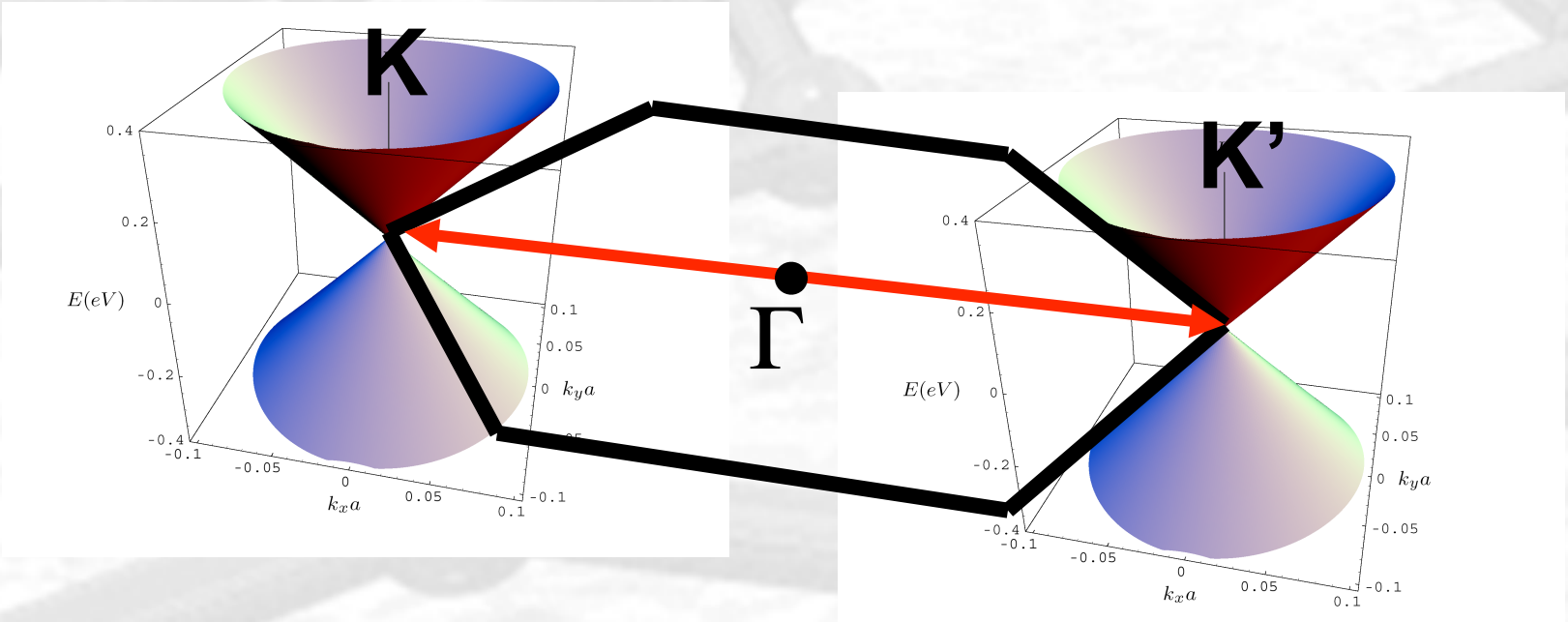

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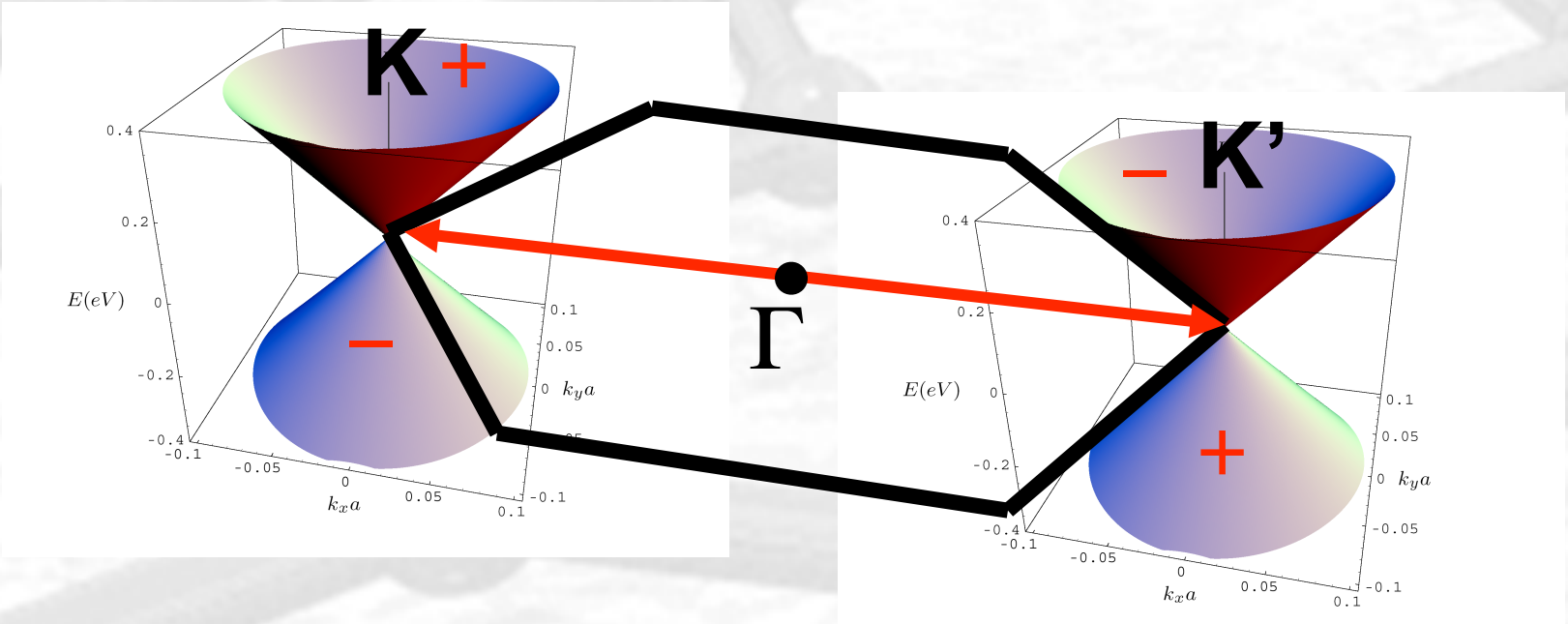

What is the proof that Dirac fermions exist in graphene?

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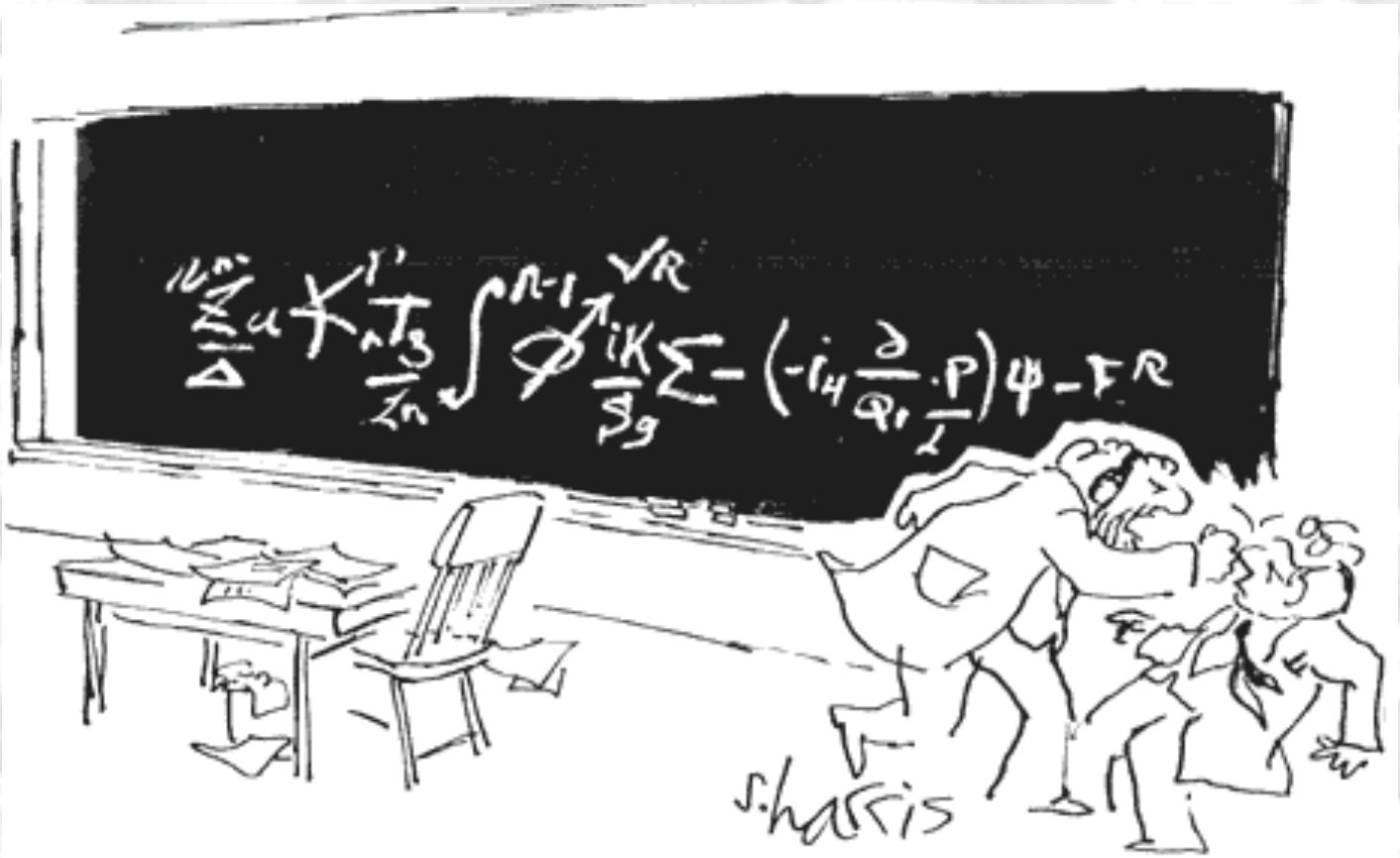


"You want proof? I'll give you proof!"

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

LETTERS

Two-dimensional gas of massless Dirac fermions in graphene

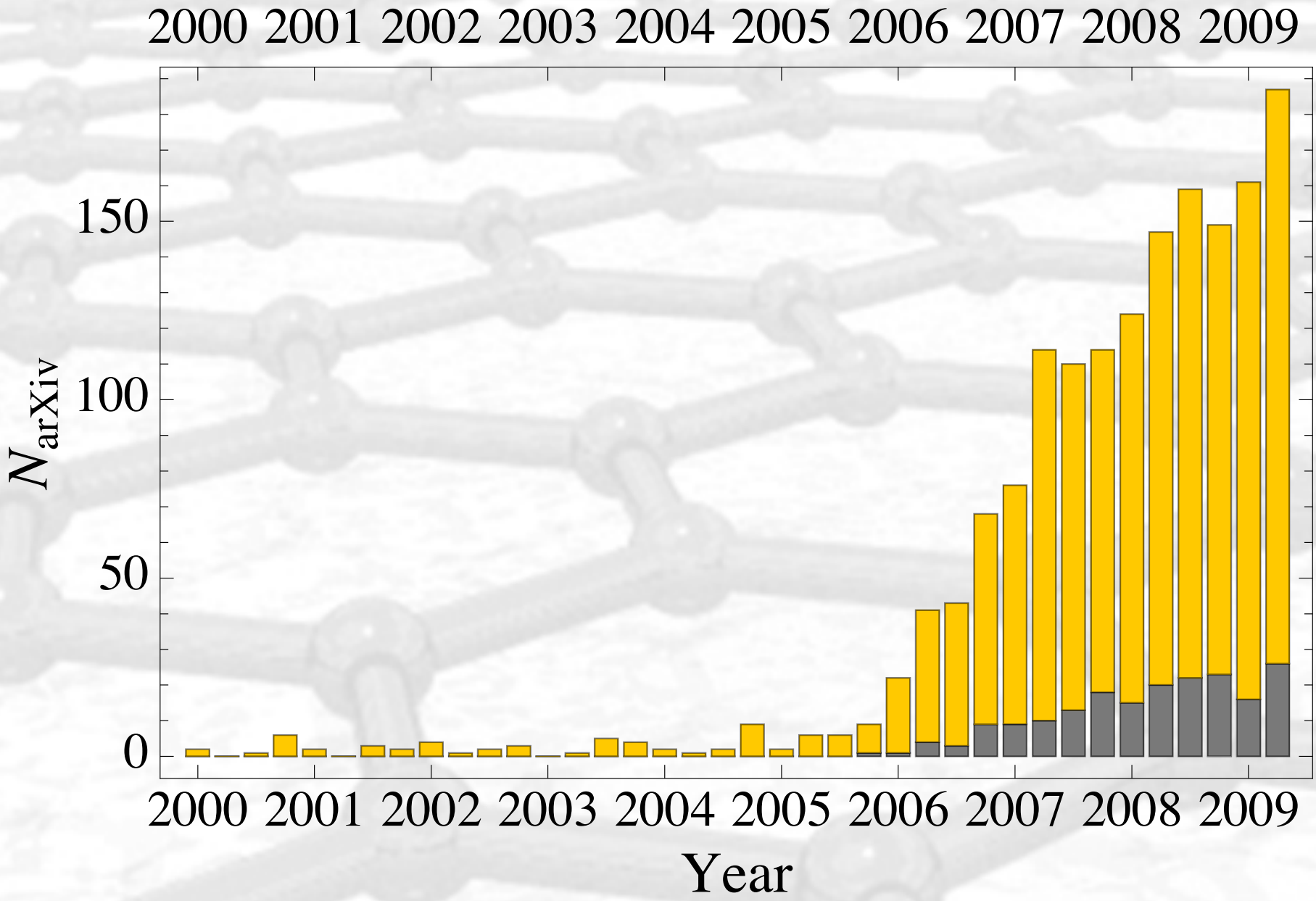
K. S. Novoselov[1], A. K. Geim[1], S. V. Morozov[2], D. Jiang[1], M. I. Katsnelson[3], I. V. Grigorieva[1], S. V. Dubonos[2] & A. A. Firsov[2]

Vol 438|10 November 2005|doi:10.1038/nature04235 nature

LETTERS

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

Yuanbo Zhang[1], Yan-Wen Tan[1], Horst L. Stormer[1,2] & Philip Kim[1]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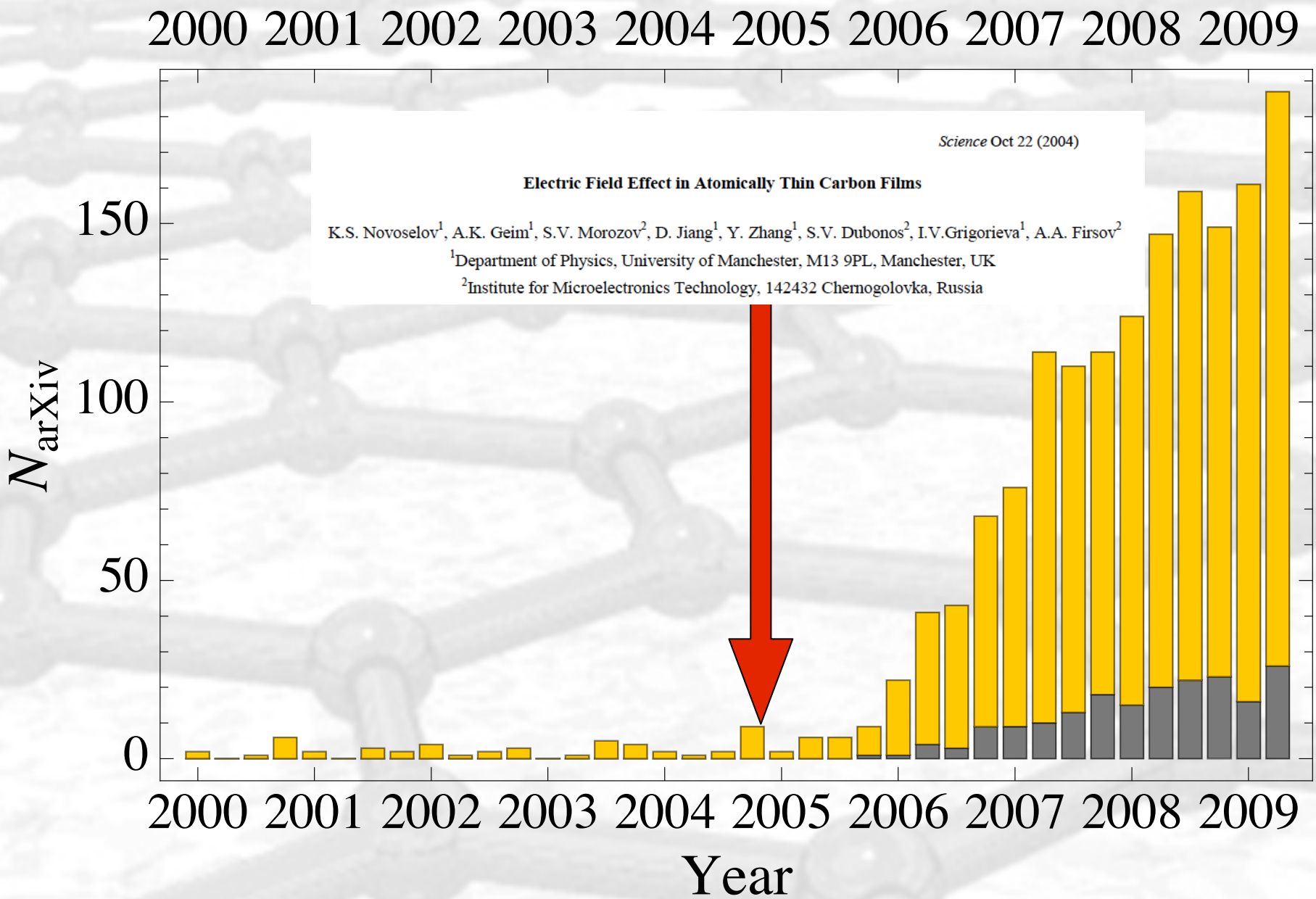
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2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
Year
Science Oct 22 (2004)
Electric Field Effect in Atomically Thin Carbon Films
K.S. Novoselov[1], A.K. Geim[1], S.V. Morozov[2], D. Jiang[1], Y. Zhang[1], S.V. Dubonos[2], I.V.Grigorieva[1], A.A. Firsov[2]
[1]Department of Physics, University of Manchester, M13 9PL, Manchester, UK
[2]Institute for Microelectronics Technology, 142432 Chernogolovka, Russia

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Topic=(graphene)

Timespan=1995-2009. Databases=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH.

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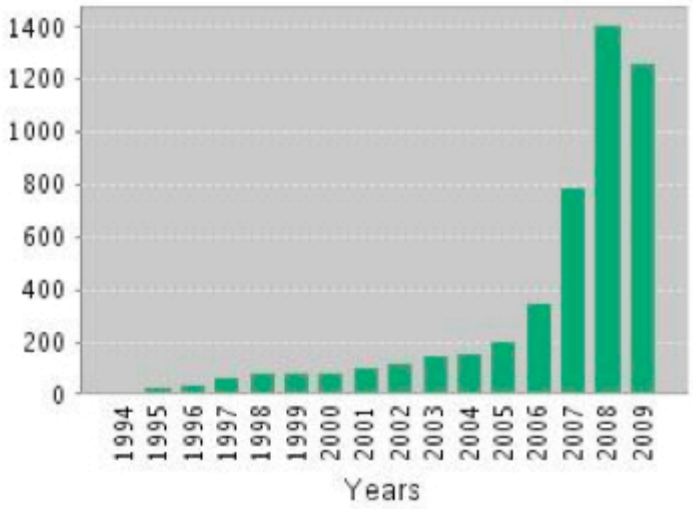
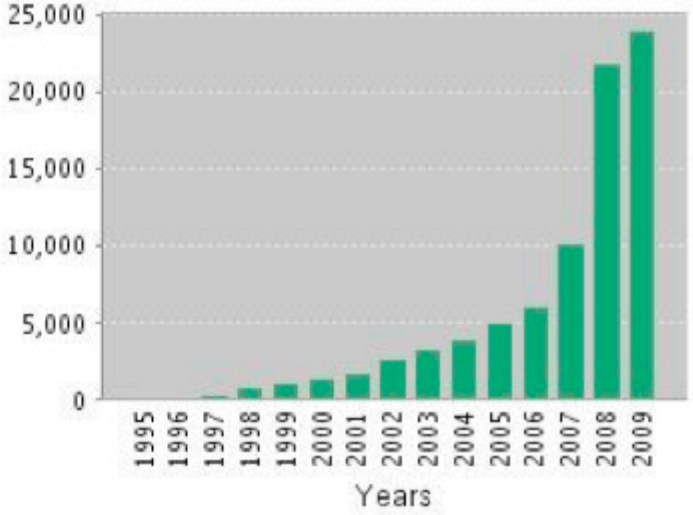


Citations in Each Year



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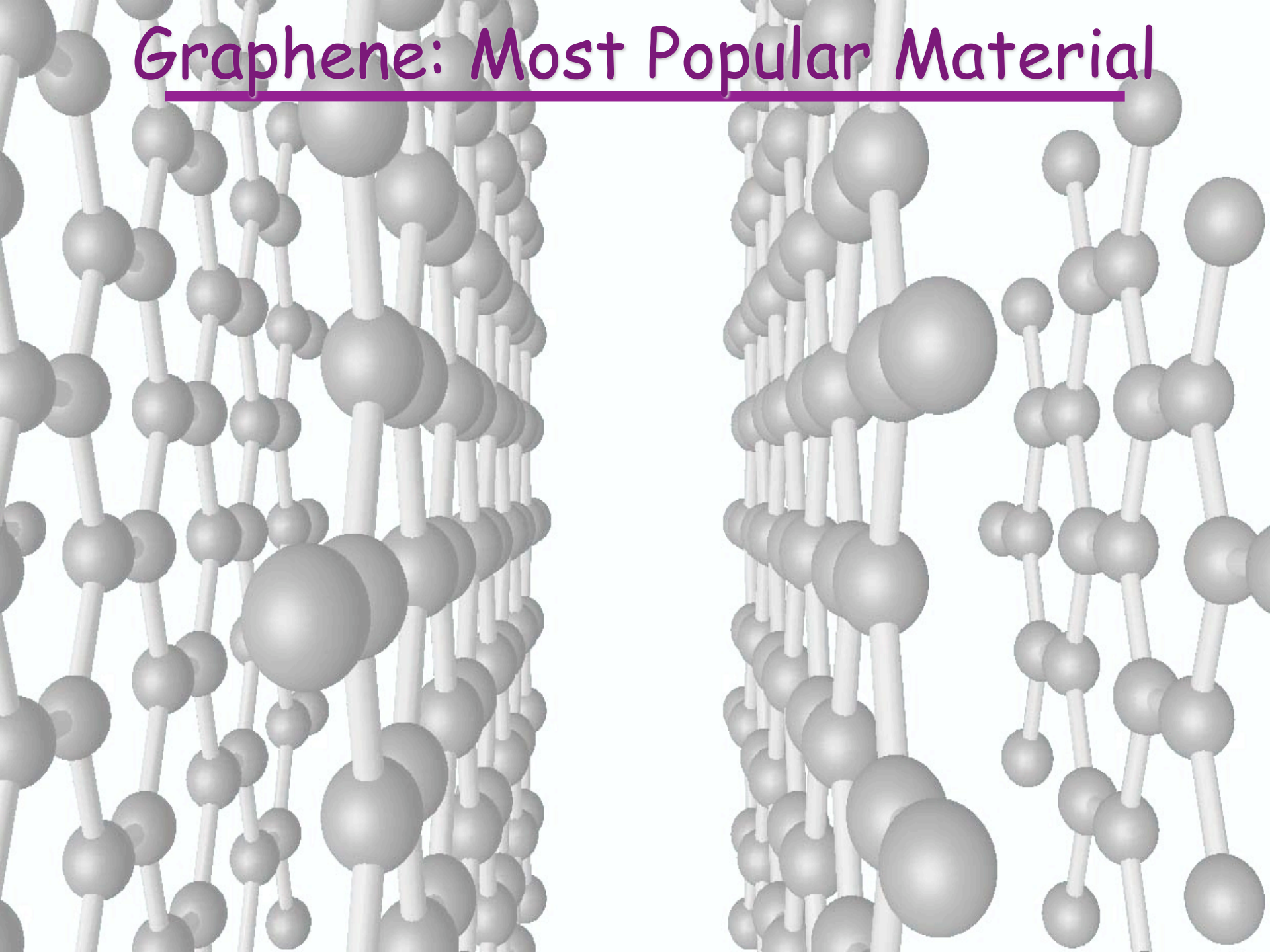
Graphene: Most Popular Material



Graphene: Most Popular Material

rank	search word	frequency

searches on all Nature websites during 2009

courtesy of Dr Peter Rogers (editor of Nature)

Graphene: Most Popular Material

rank	search word	frequency
5	obesity	1.0

searches on all Nature websites during 2009

courtesy of Dr Peter Rogers (editor of Nature)

Graphene: Most Popular Material

rank	*search word*	*frequency*
2	cancer	~2.0
3	HIV	1.3
4	apoptosis	1.03
5	obesity	1.0

searches on all Nature websites during 2009

courtesy of Dr Peter Rogers (editor of Nature)

Graphene: Most Popular Material

rank	*search word*	*frequency*
1	graphene	~3.0
2	cancer	~2.0
3	HIV	1.3
4	apoptosis	1.03
5	obesity	1.0

searches on all Nature websites during 2009

courtesy of Dr Peter Rogers (editor of Nature)

$$E(p) = \pm v\, p$$

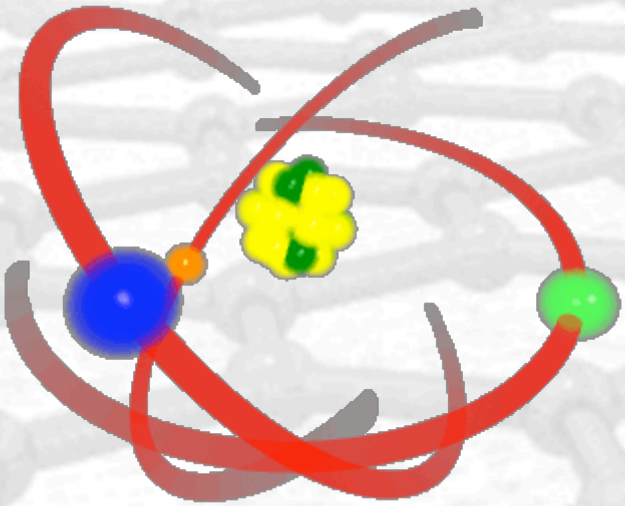
$$v = c/300$$

Electrons behave as massless relativistic particles.

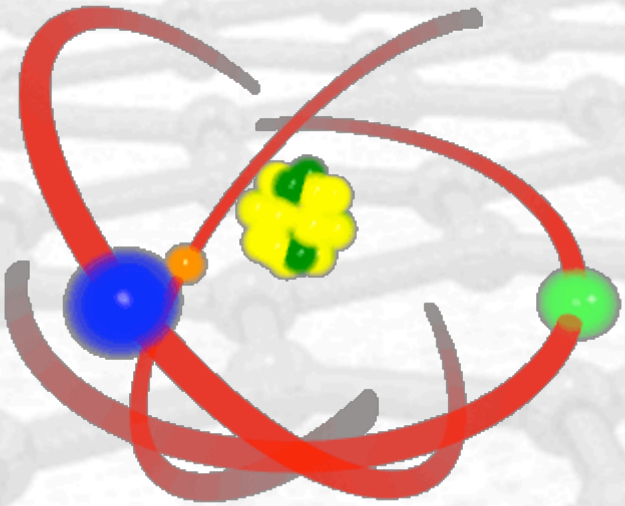
Relativity at very low "speed of light"

Quantum Physics plus Relativity on a table-top !

Atomic Physics

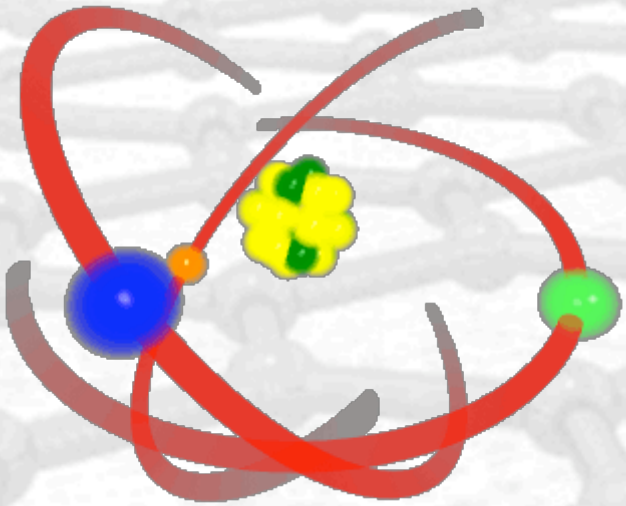


Atomic Physics



$$V(r) = -Z\frac{e^2}{\varepsilon_0}\frac{1}{r} \quad \text{Coulomb law}$$

Atomic Physics



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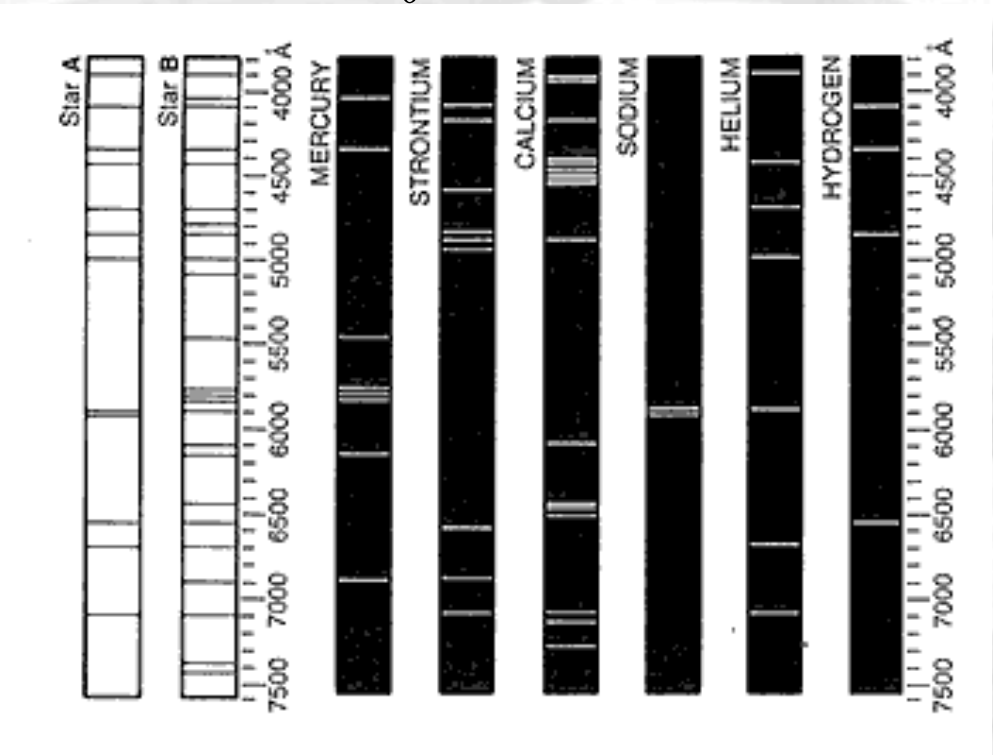
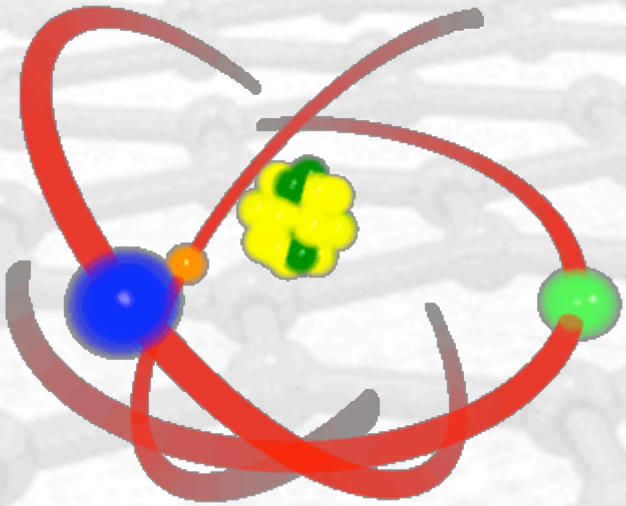


Atomic Physics



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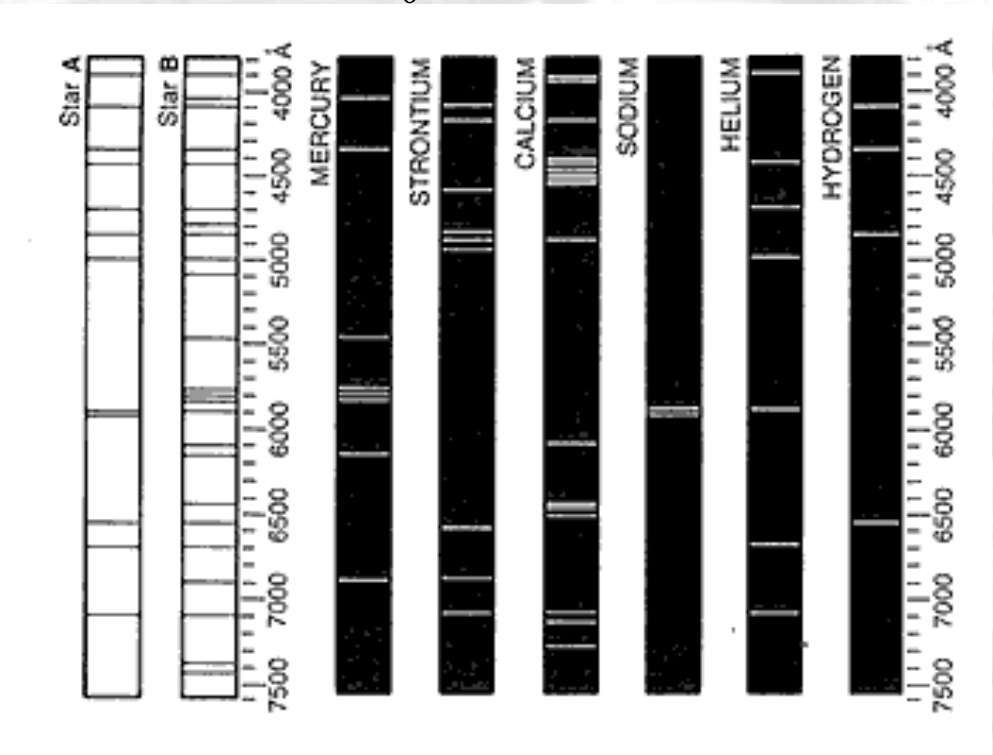
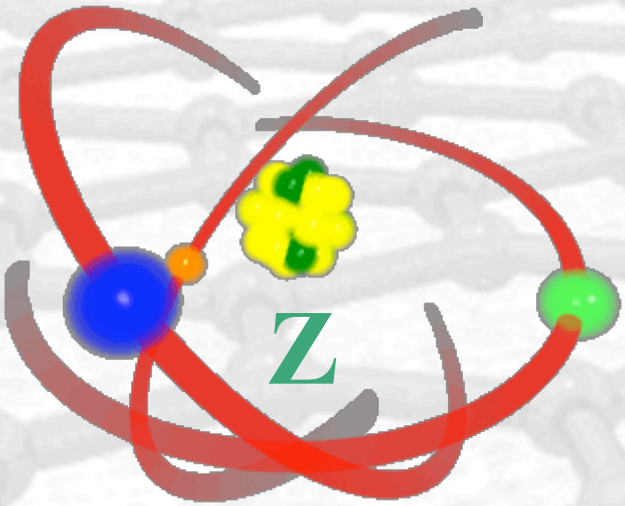


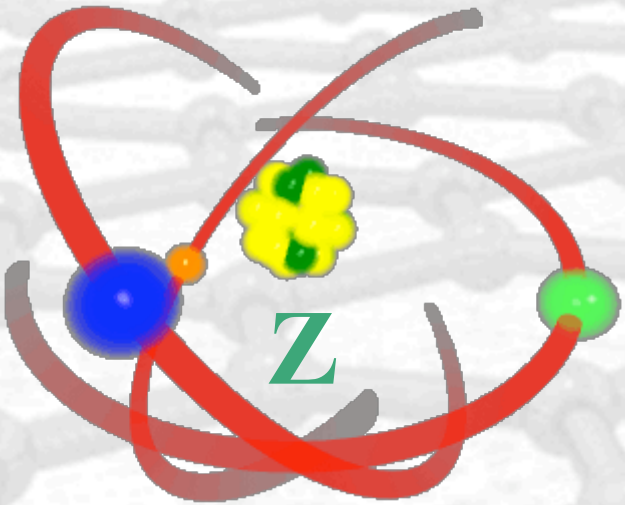
Fine structure constant

$$\alpha = \frac{e^2}{\varepsilon_0 hc} = 0.007297352536(5) \approx \frac{1}{137}$$

Atomic Physics

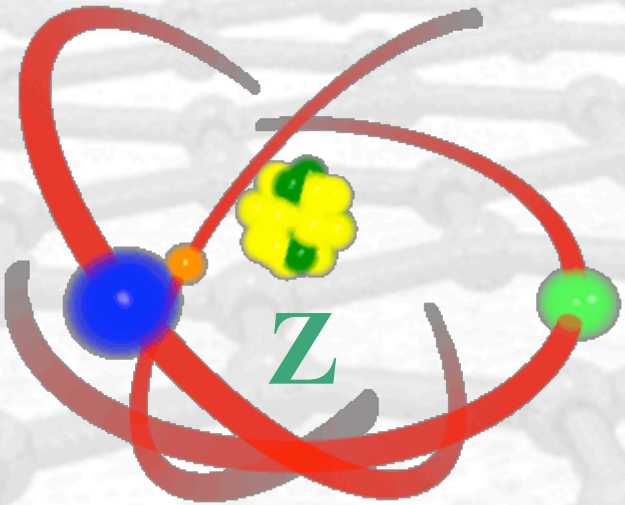


Atomic Physics



$$Z < \frac{1}{\alpha} \approx 137$$

Atomic Physics



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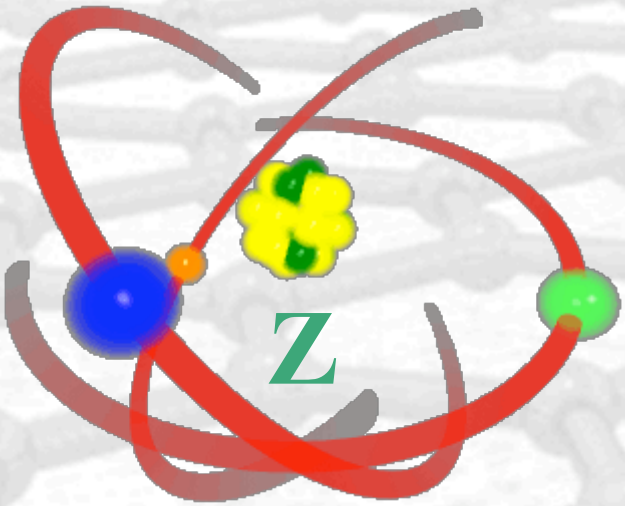


$$Z < \frac{1}{\alpha} \approx 137$$

Z

$$Z > \frac{1}{\alpha} \approx 137$$

Overcritical Atom

Z

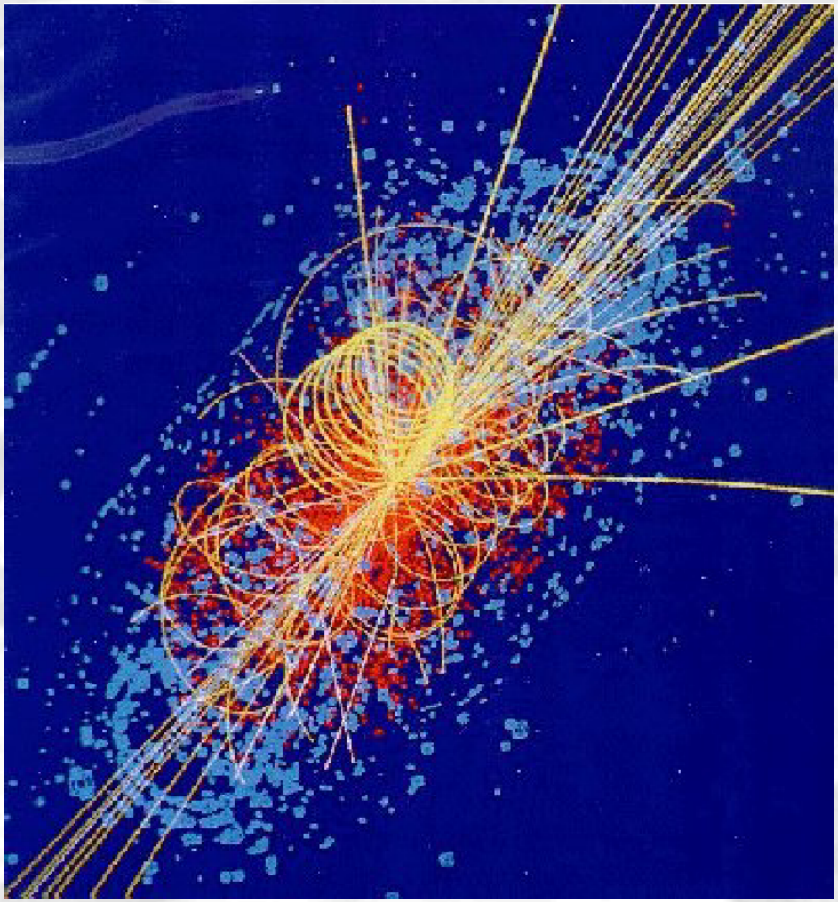
Positron emission

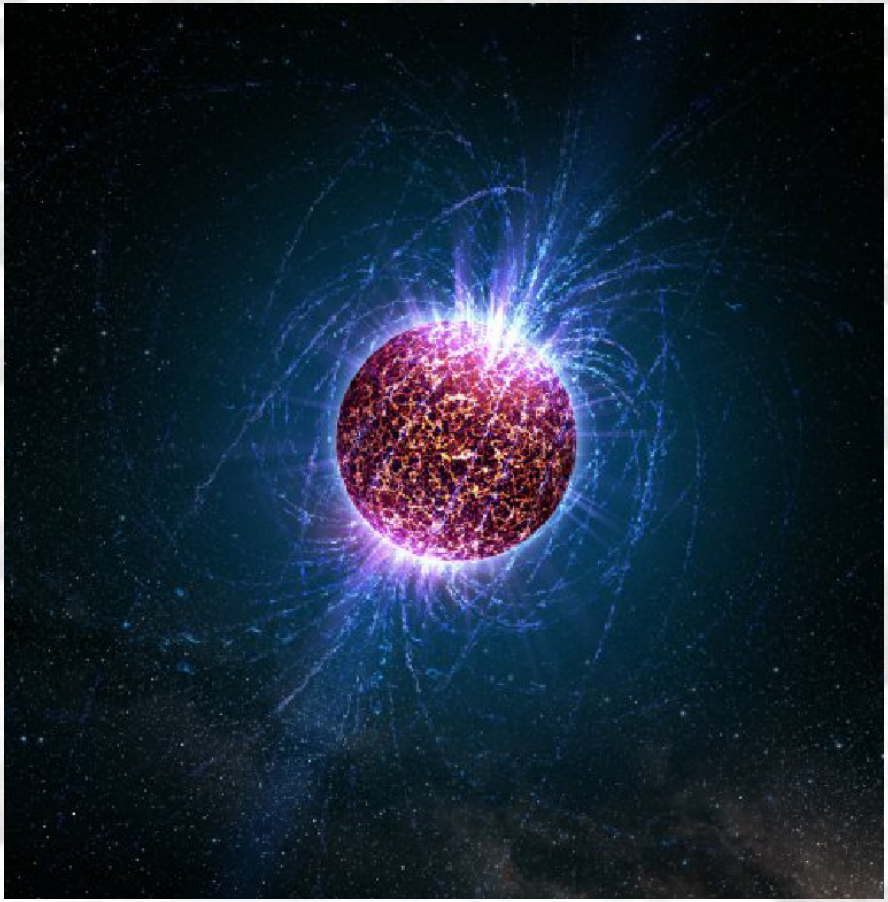
Periodic table of the elements

- alkali metals
- alkaline earth metals
- transition metals
- other metals
- other nonmetals
- halogens
- noble gases
- rare earth elements (21, 39, 57–71)
  lanthanide elements (57–71 only)
- actinide elements

period	group 1* Ia**	2 IIa	3 IIIb	4 IVb	5 Vb	6 VIb	7 VIIb	8	9 VIIIb	10	11 Ib	12 IIb	13 IIIa	14 IVa	15 Va	16 VIa	17 VIIa	18 0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 *** (Uub)	113 *** (Uut)	114 *** (Uuq)	115 *** (Uup)	116 *** (Uuh)		
lanthanide series 6				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
actinide series 7				90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

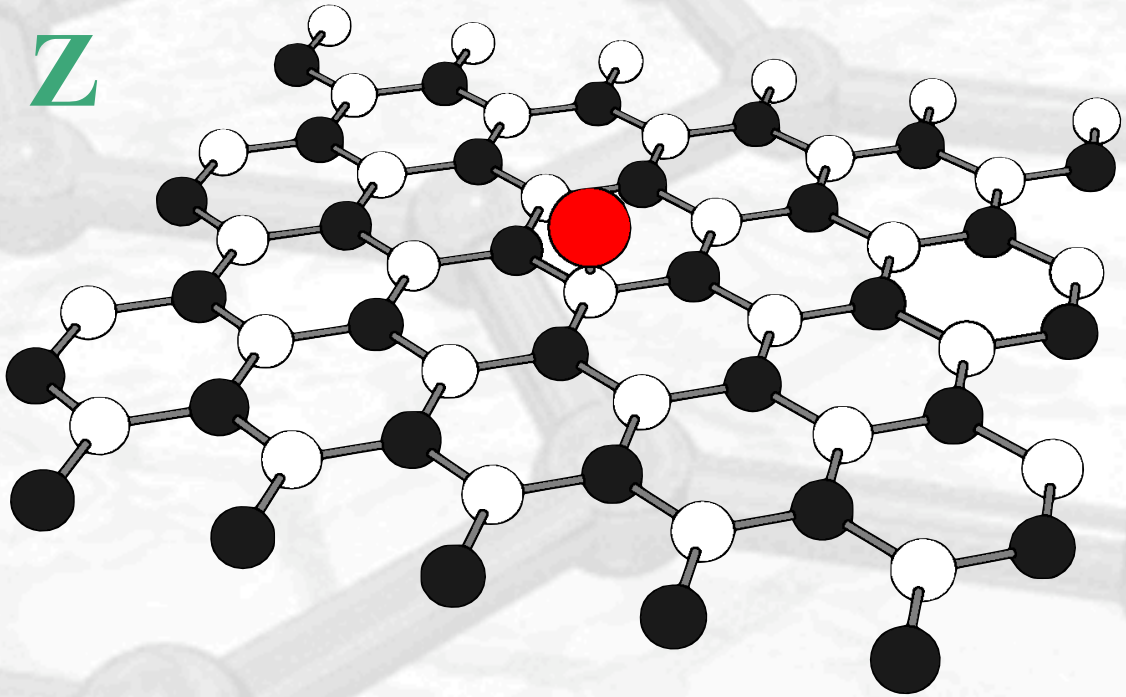
* Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC).
** Numbering system widely used, especially in the U.S., from the mid-20th century.
*** Discoveries of elements 112–116 are claimed but not confirmed. Element names and symbols in parentheses are temporarily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





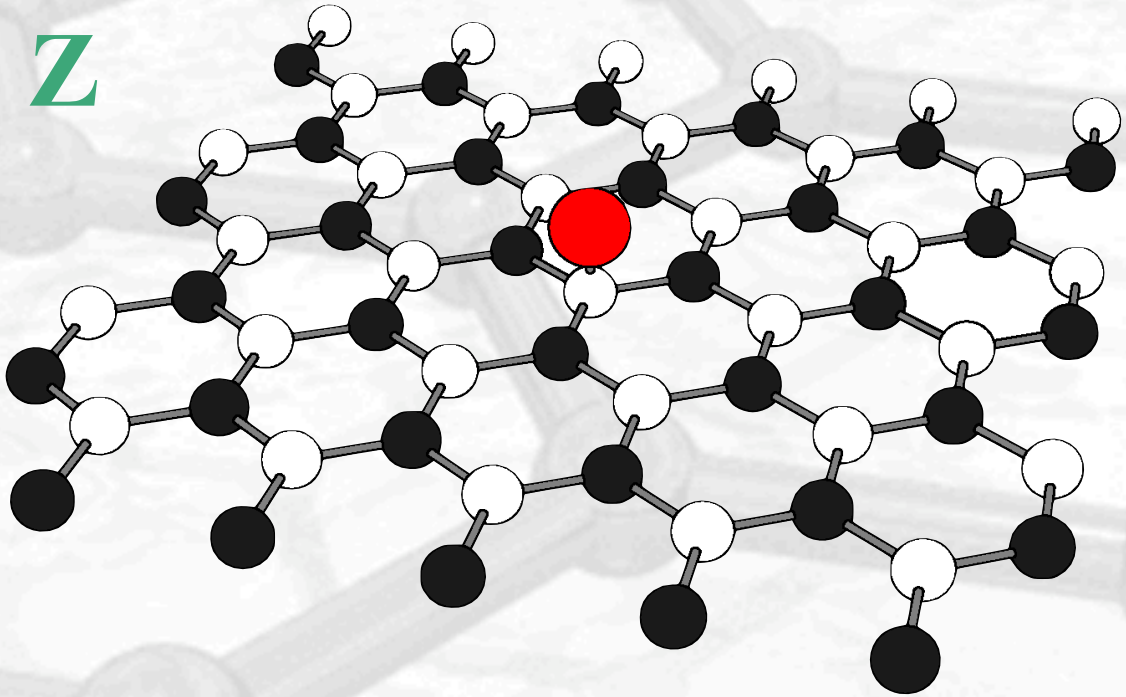
heavy ion collisions **neutron stars**

But in graphene:



But in graphene:

$$\alpha_G = \frac{e^2}{\varepsilon_0 h v} \approx 2$$



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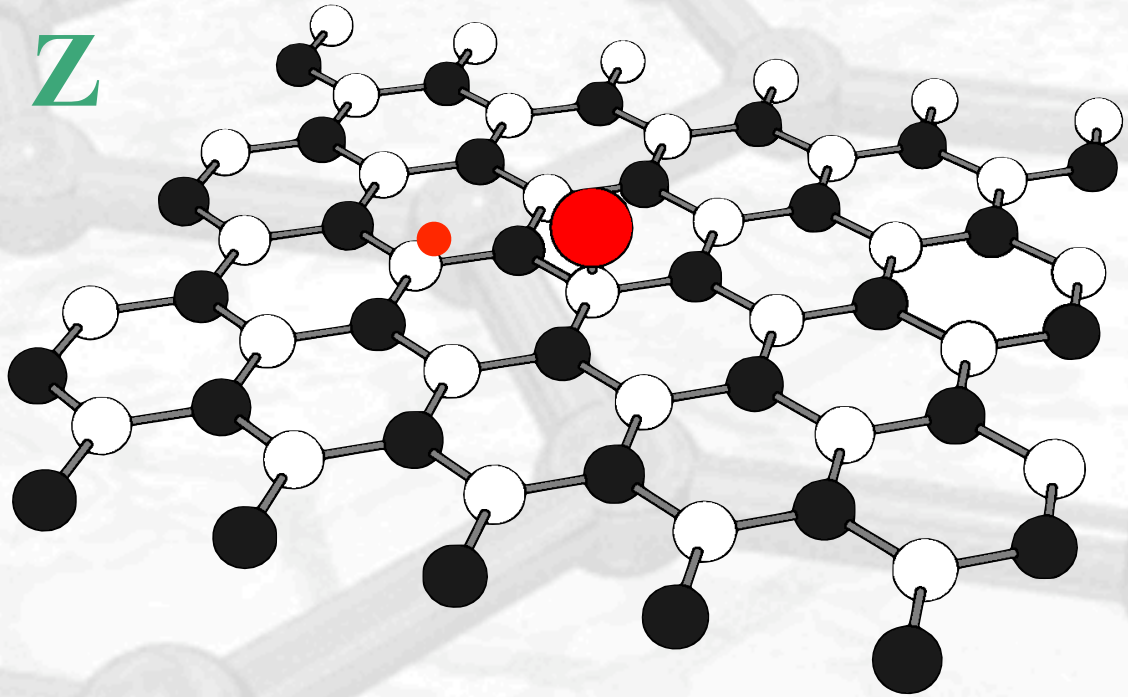
Atoms become overcritical easily

$$Z > \frac{1}{\alpha_G} \approx 0.5$$

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



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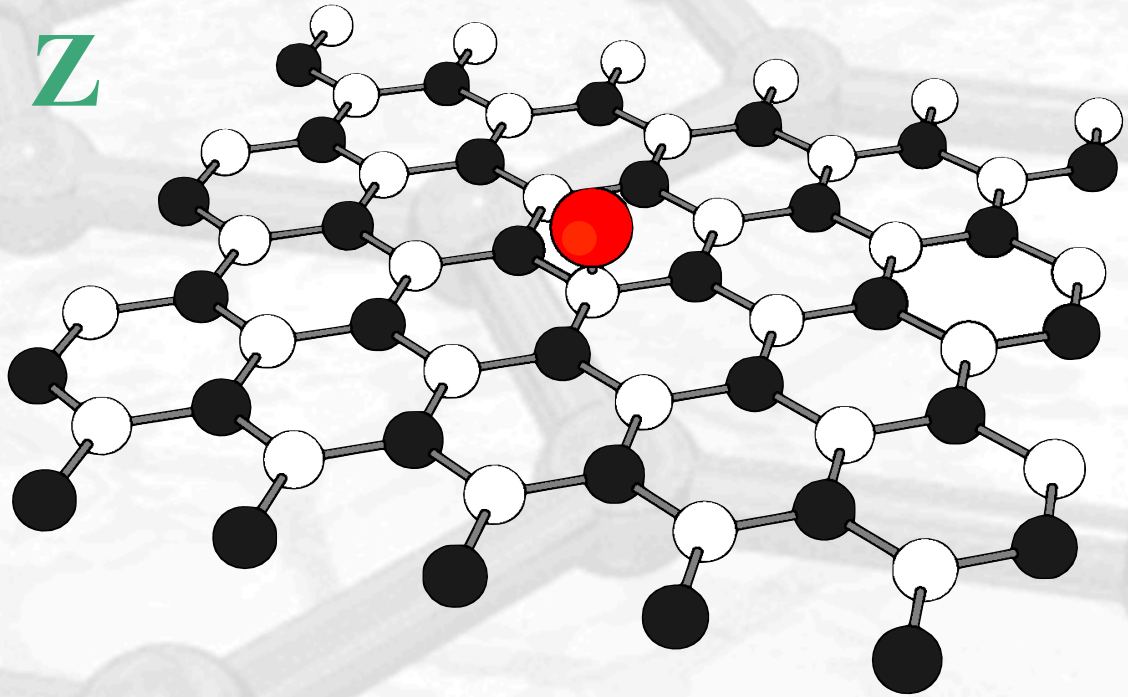
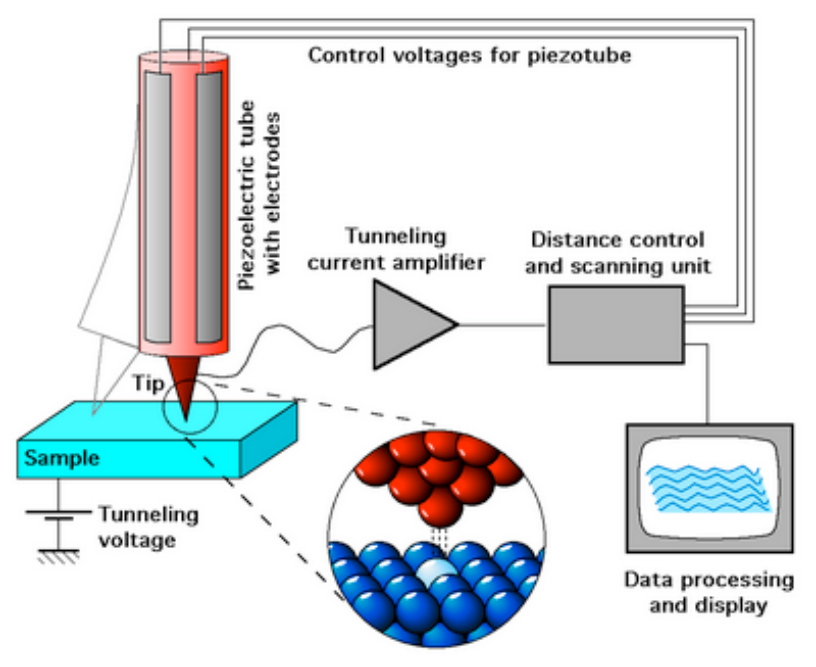
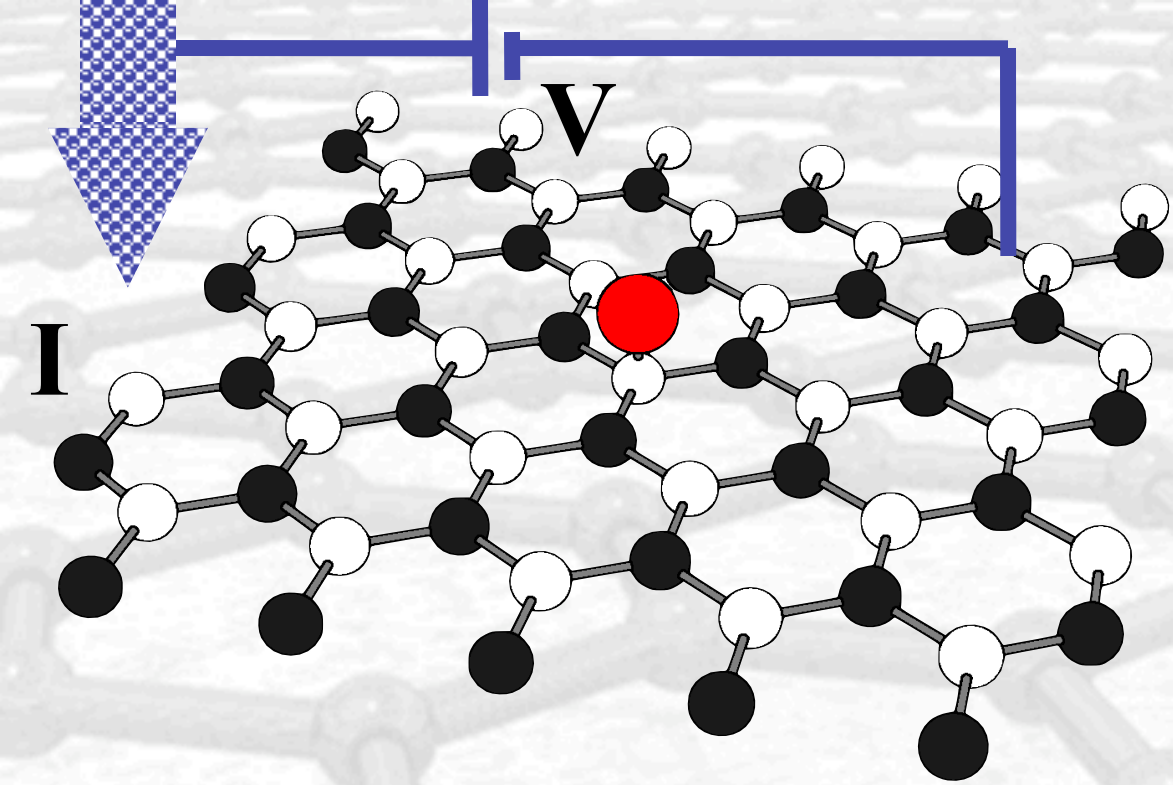




Use a scanning tunneling microscope,for a “high-energy experiment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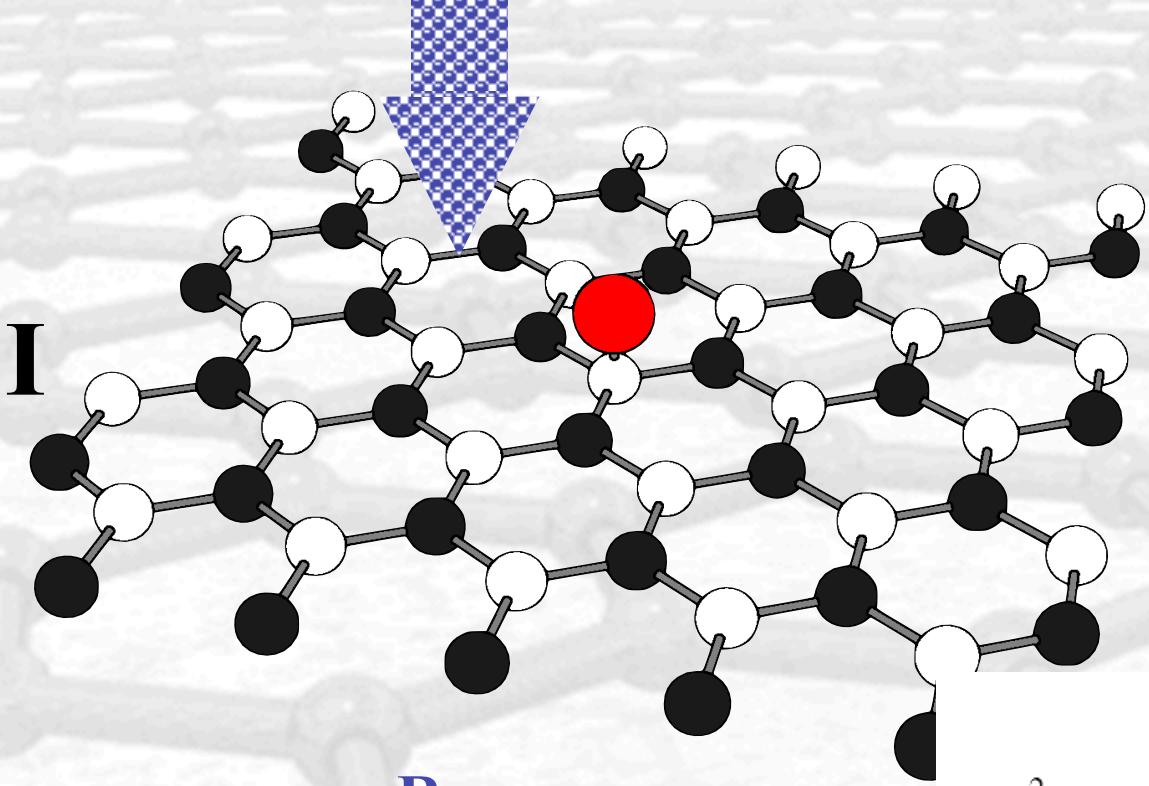
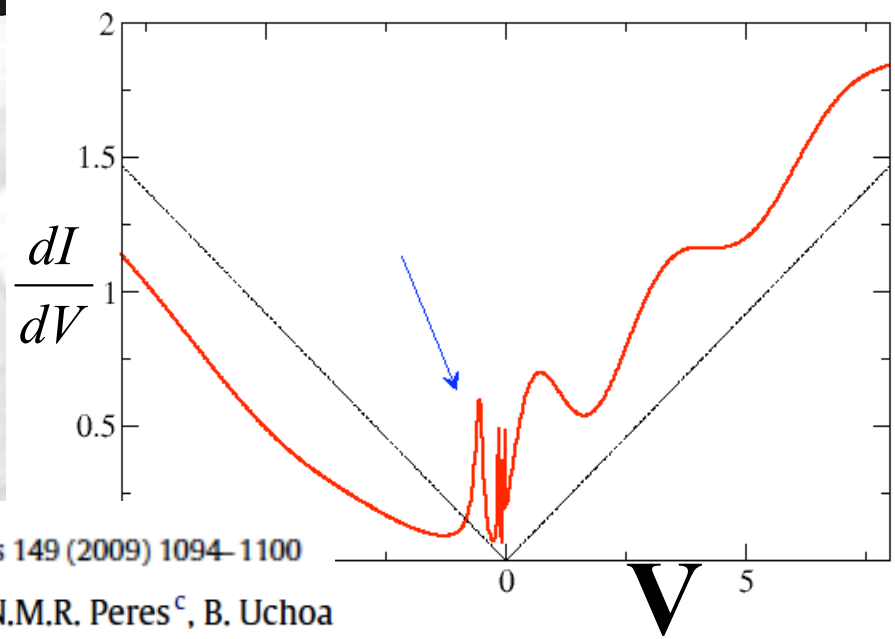


Resonances indicate emission of anti-particles

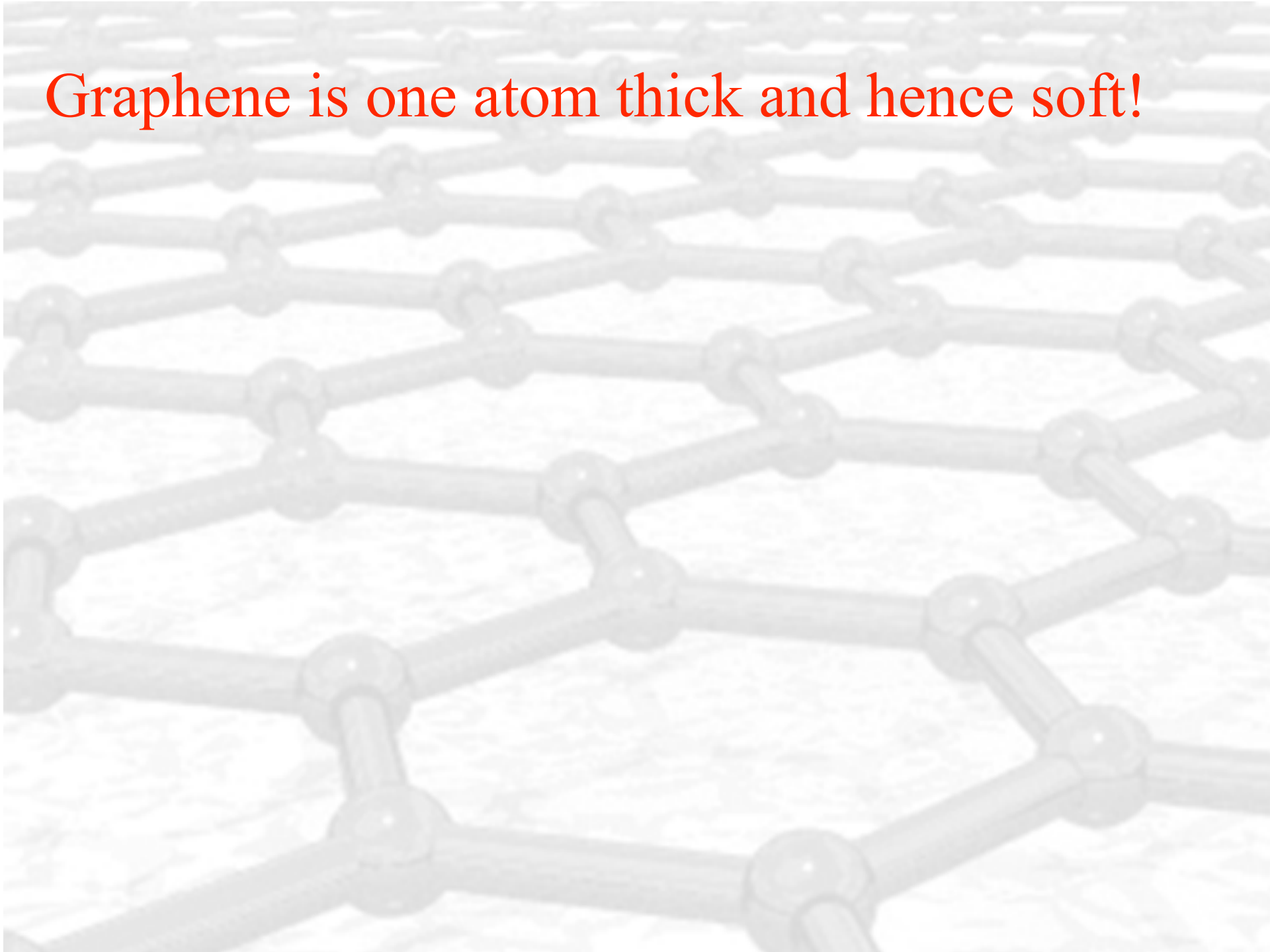


Adatoms in graphene

Solid State Communications 149 (2009) 1094–1100

A.H. Castro Neto [a,*], V.N. Kotov [a], J. Nilsson [b], V.M. Pereira [a], N.M.R. Peres [c], B. Uchoa

Graphene is one atom thick and hence soft!



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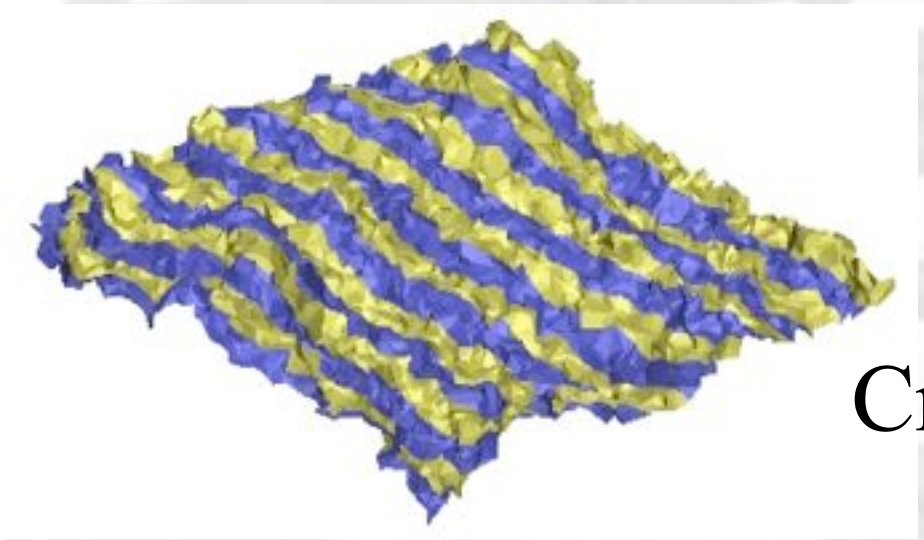
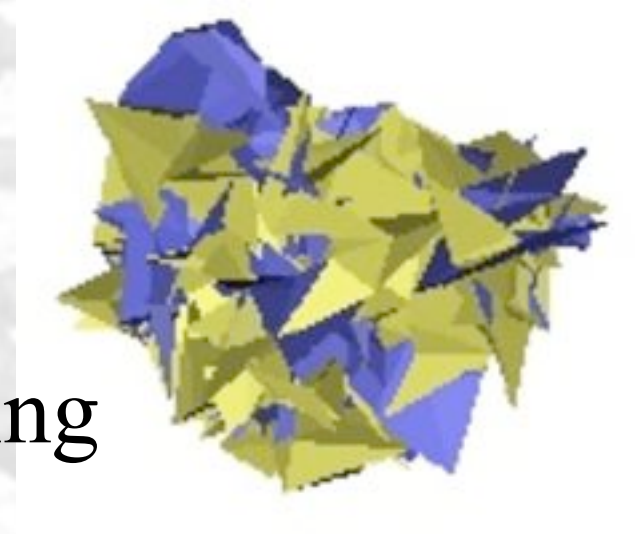


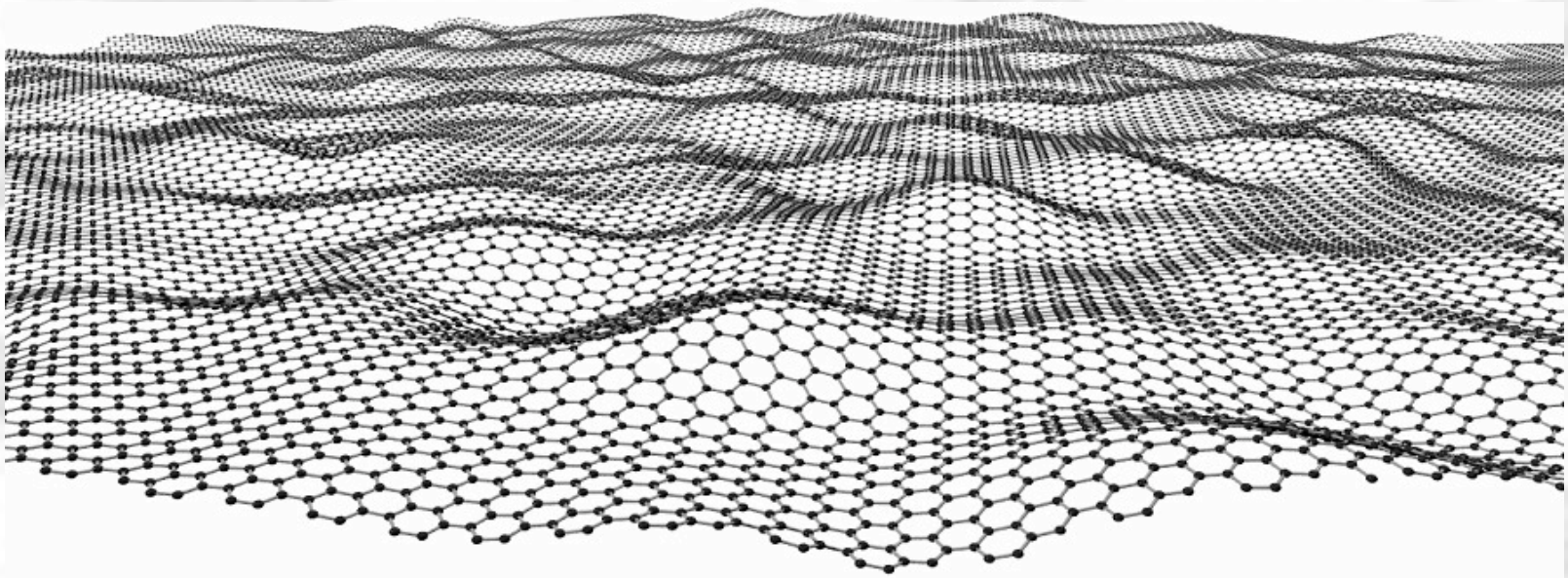
Crumpling



Nelson D., Piran D. R. and Weinberg S., Statistical Mechanics of Membranes and Surfaces (World Scientific, Singapore) 2004.

Graphene is one atom thick and hence soft!

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



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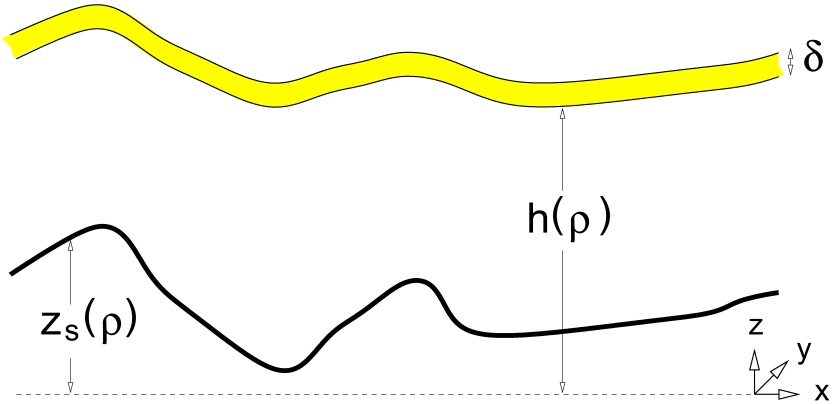
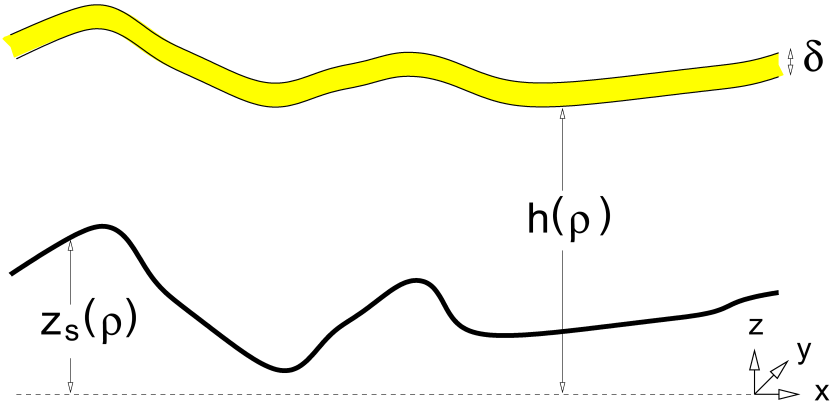
Soft and hard condensed matter of graphene

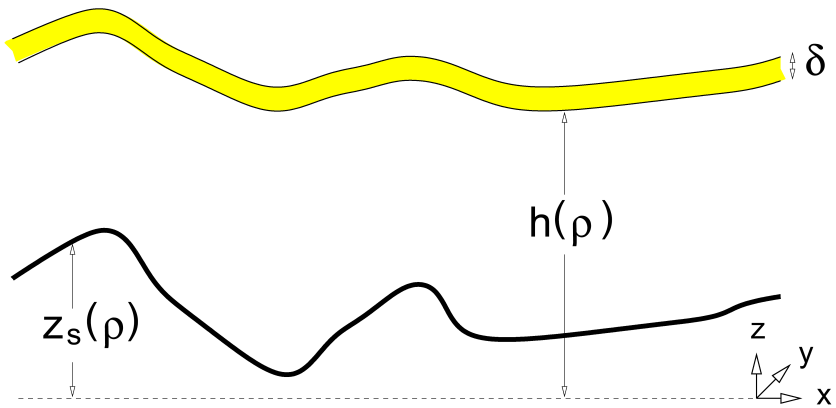


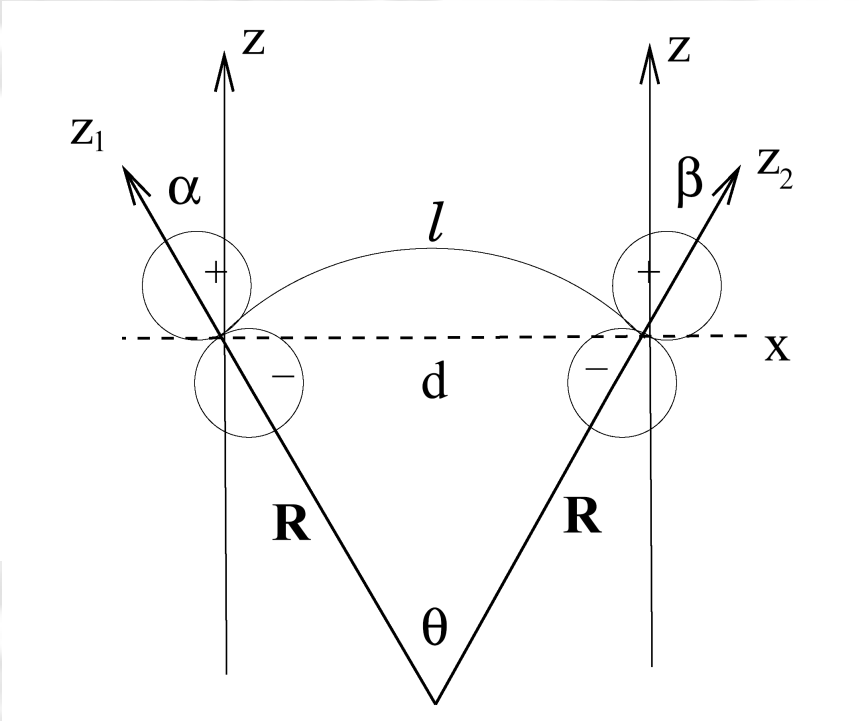
Soft and hard condensed matter of graphene



$$H_0 = i v_F \sigma \cdot \nabla$$

Soft and hard condensed matter of graphene





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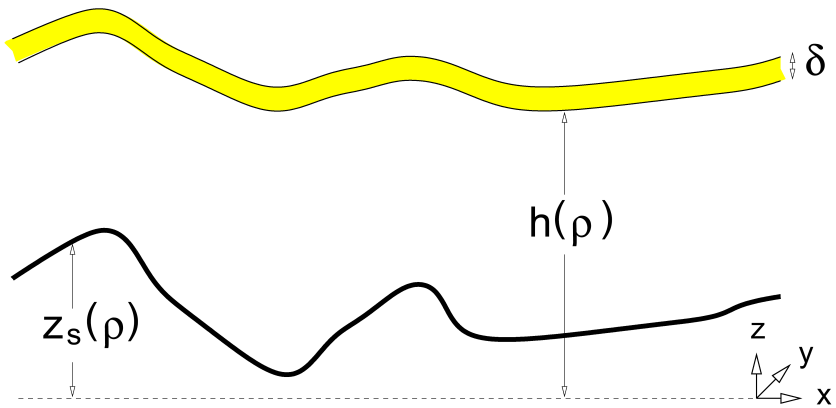
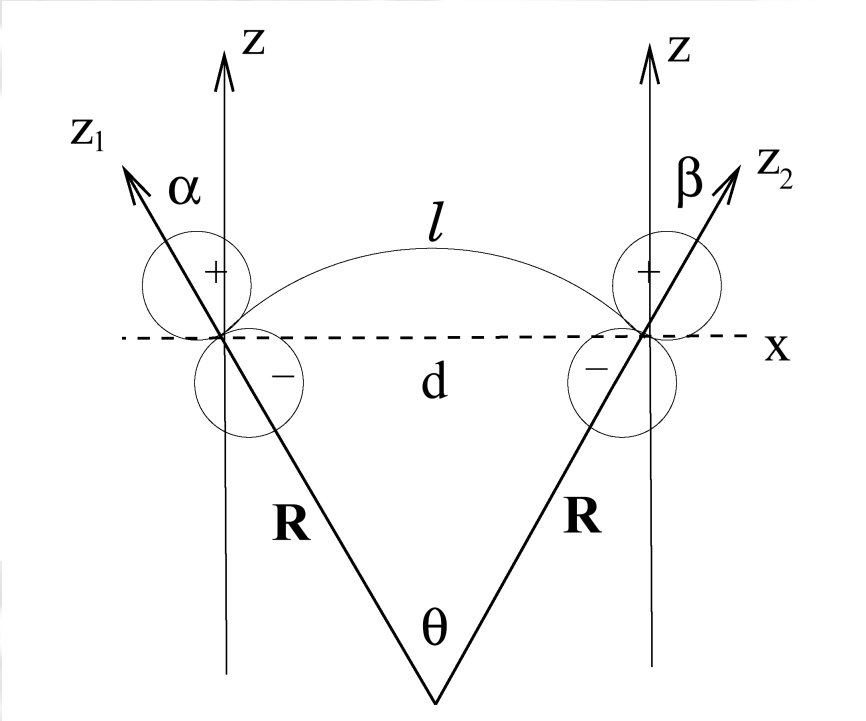
Soft and hard condensed matter of graphene





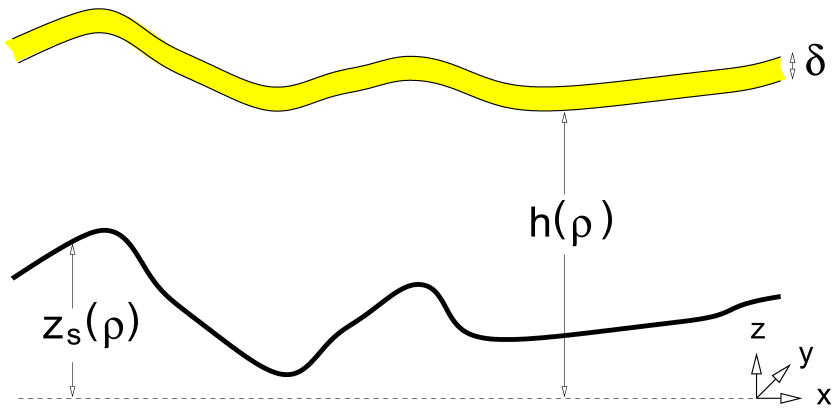
$$H_0 = i v_F \sigma \cdot \nabla$$

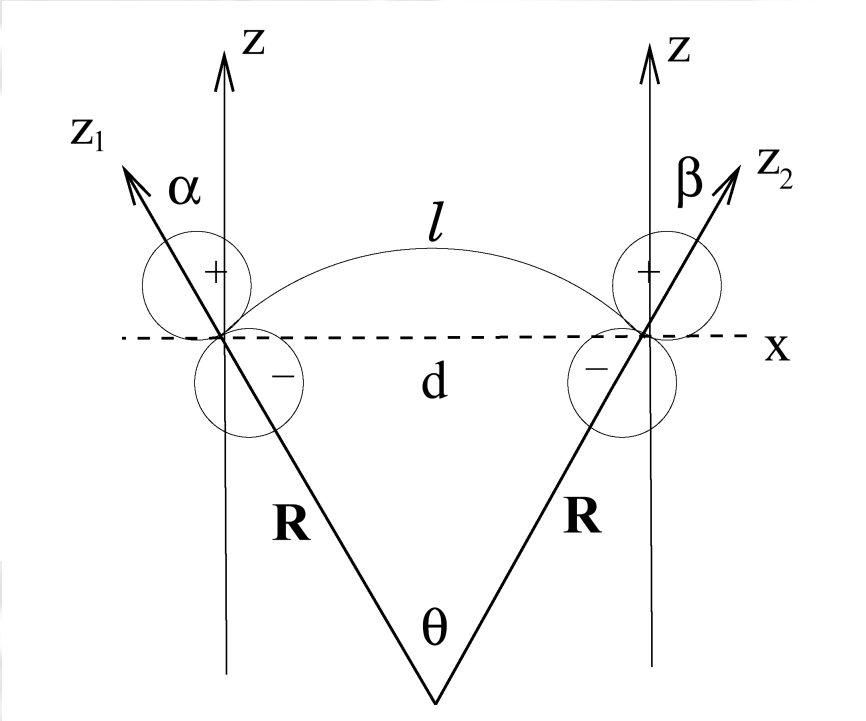
$$H_M = \sigma \cdot (i v_F \nabla + \mathcal{A}(\mathbf{r})) + \Phi(\mathbf{r})$$

$$\mathcal{A}(\mathbf{r}) \propto \frac{\mathbf{n}(\theta)}{R^2(\mathbf{r})} \qquad \langle \mathbf{n}(\theta) \rangle = 0$$

$$\Phi(\mathbf{r}) \propto \frac{1}{R^2(\mathbf{r})}$$

Soft and hard condensed matter of graphene





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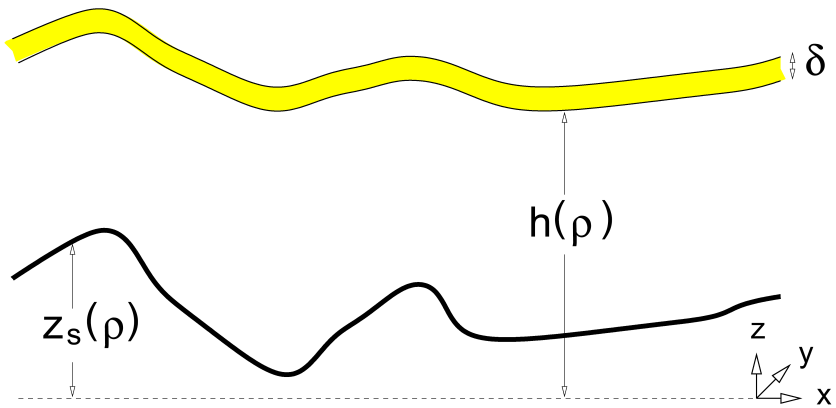
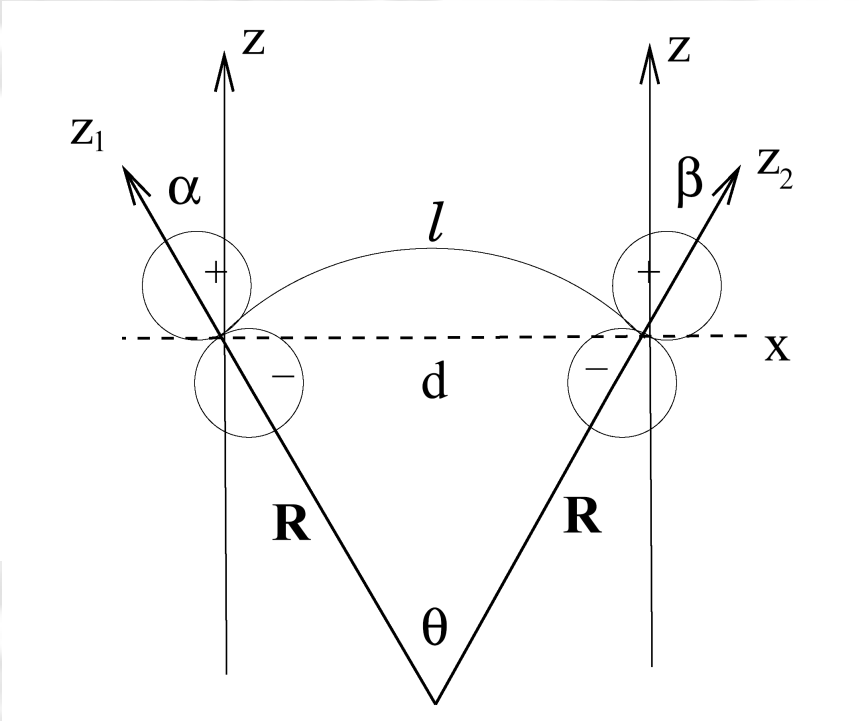
Soft and hard condensed matter of graphene





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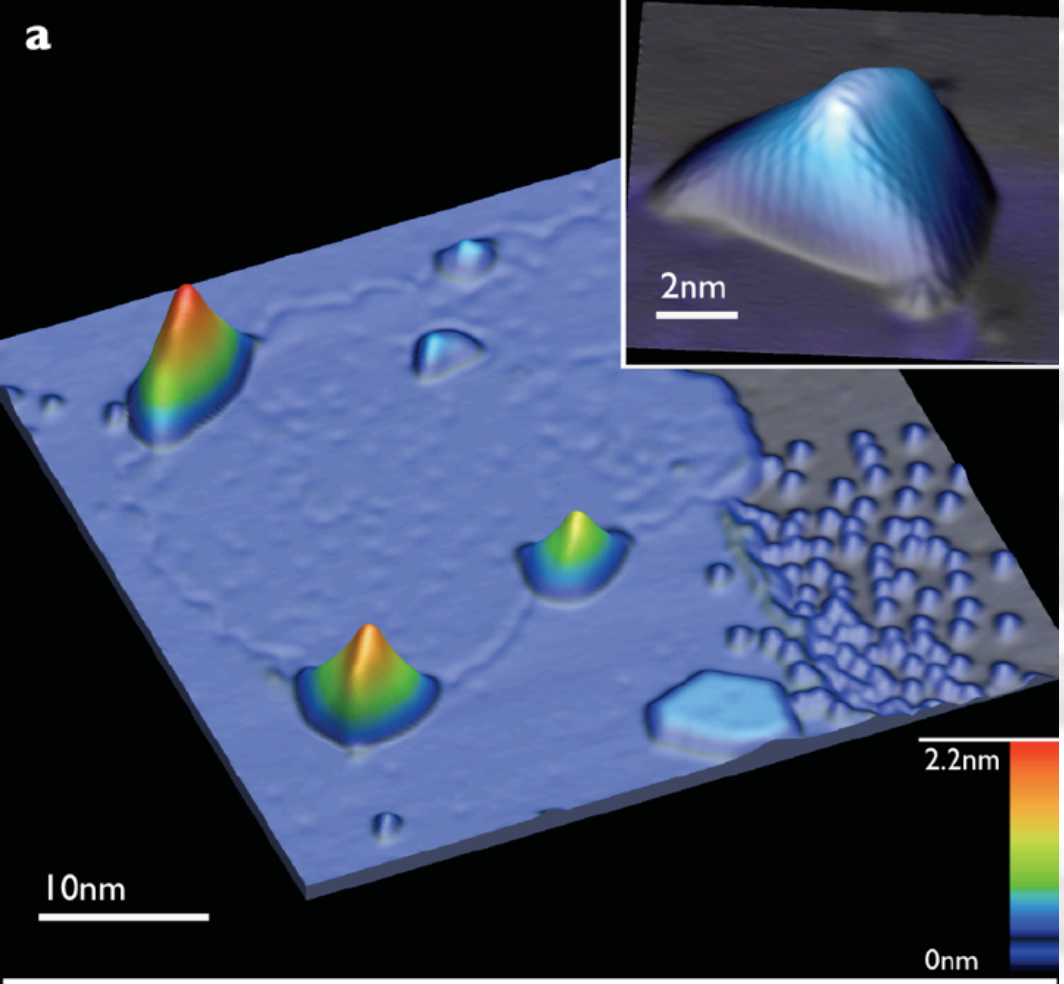
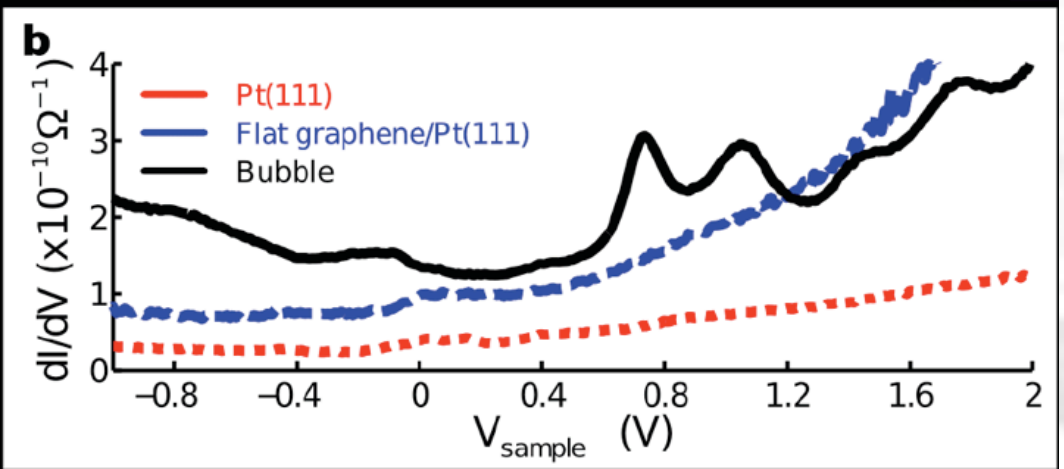
$$\Phi(\mathbf{r}) \propto \frac{1}{R^2(\mathbf{r})} \qquad \mathbf{B} = \nabla \times \mathbf{A}$$

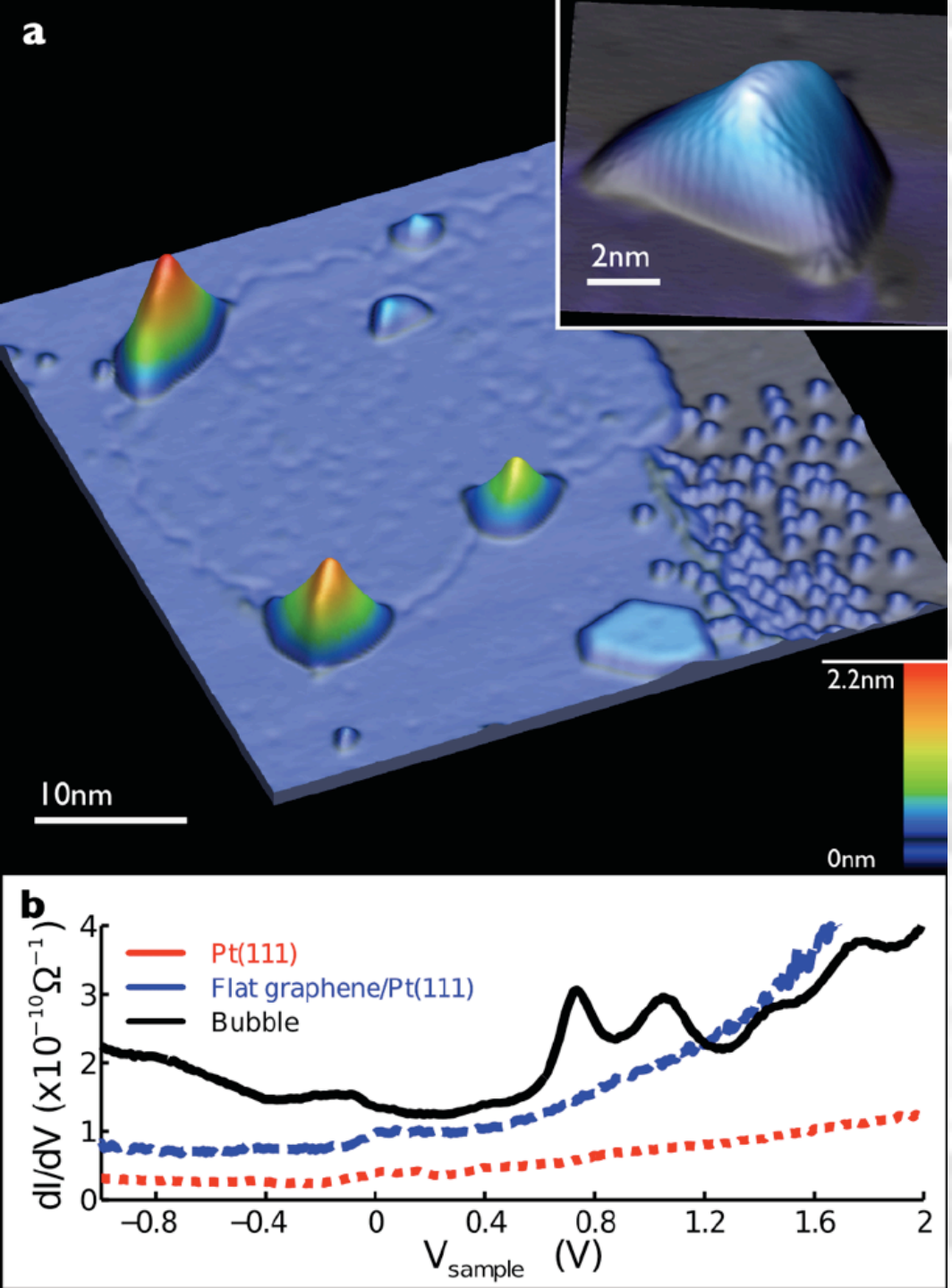
Graphene is a metallic membrane

Eun-Ah Kim, and A. H. Castro Neto, Europhysics Letters 84, 57007 (2008)

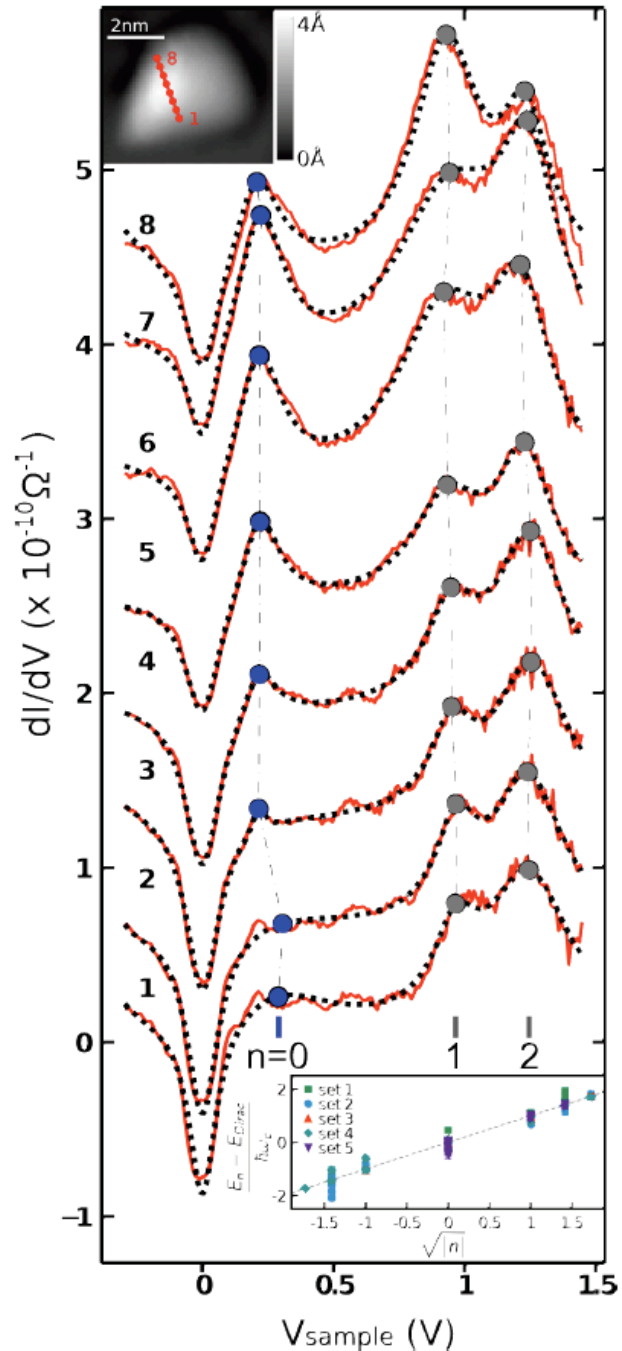




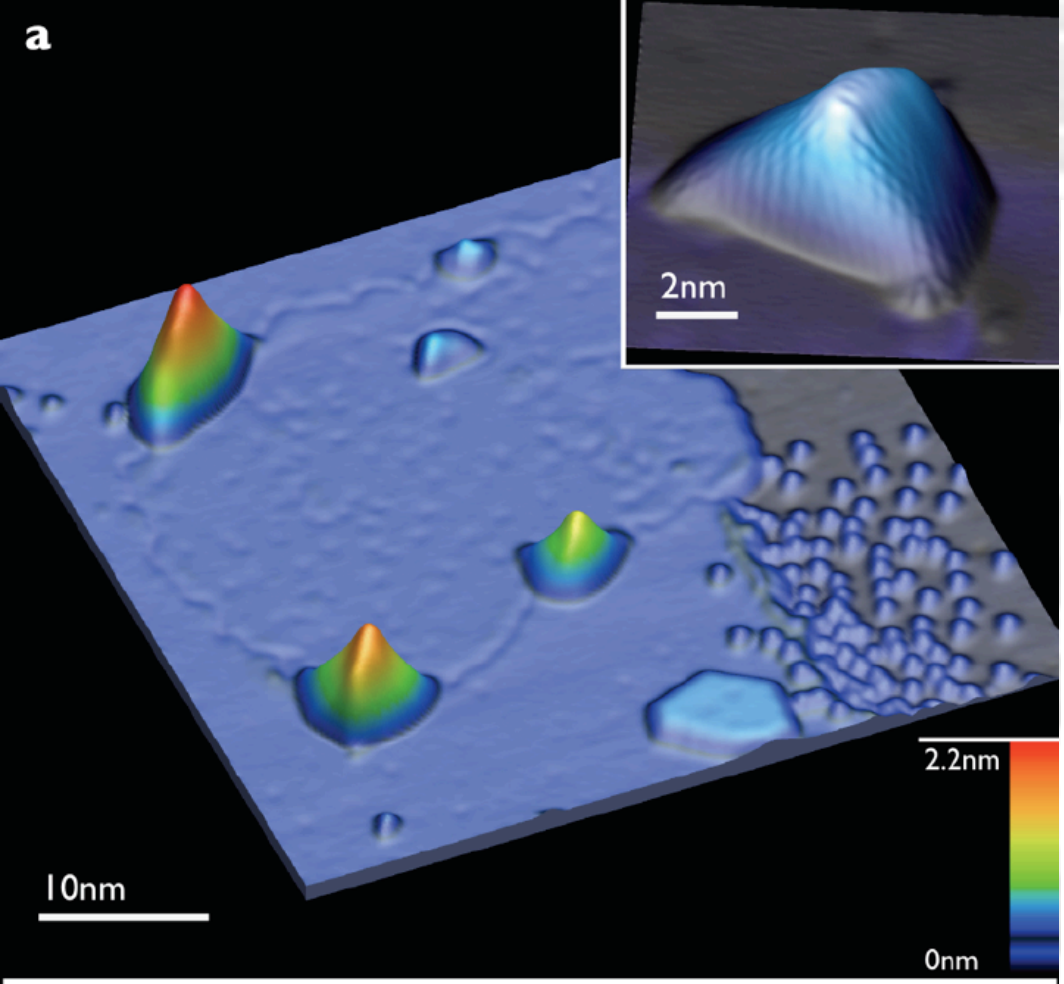
N. Levy, S.A. Burke, K.L. Meaker, M. Panlasigui, A. Zettl, F. Guinea, A.H. Castro Neto, and M.F. Crommie, unpublished.

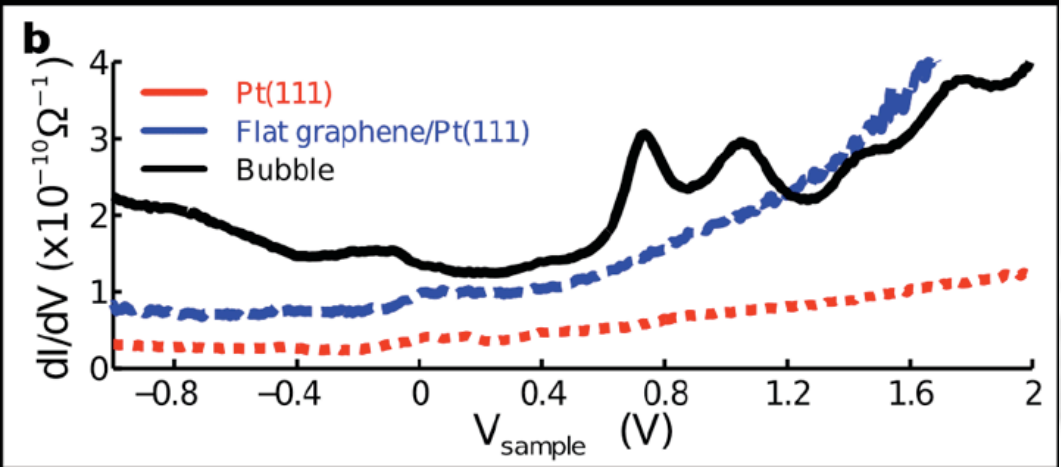

a
2nm
10nm
2.2nm
0nm
b
Pt(111)
Flat graphene/Pt(111)
Bubble
dI/dV (x10^{-10}Ω^{-1})
V$_{sample}$ (V)

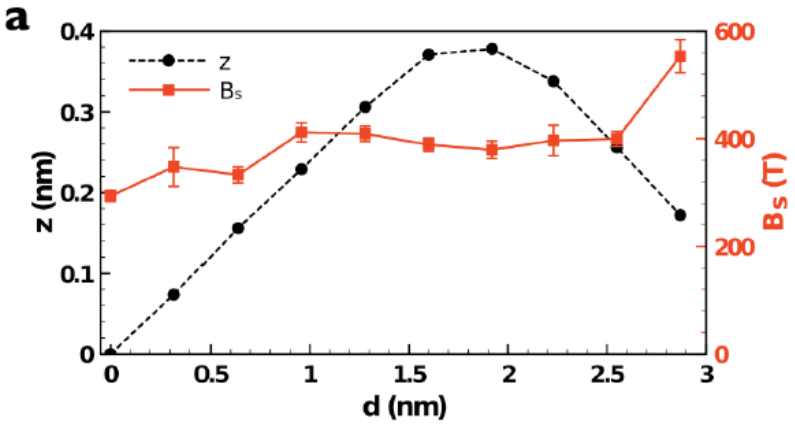
N.
A. ie,
unp

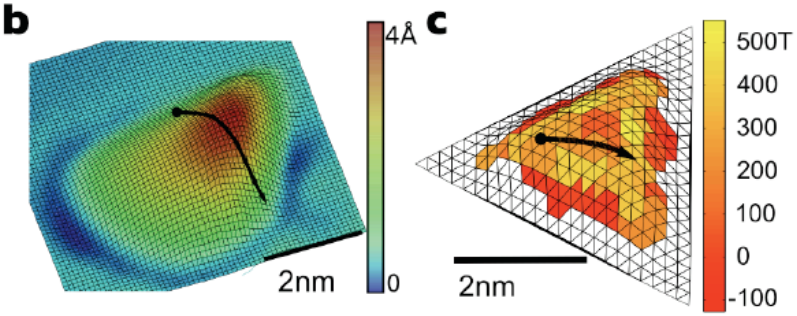

2nm
4Å
0Å
8
1
dI/dV (x 10^{-10}Ω^{-1})
n=0
1
2
set 1
set 2
set 3
set 4
set 5
$\sqrt{n}$
V$_{sample}$ (V)

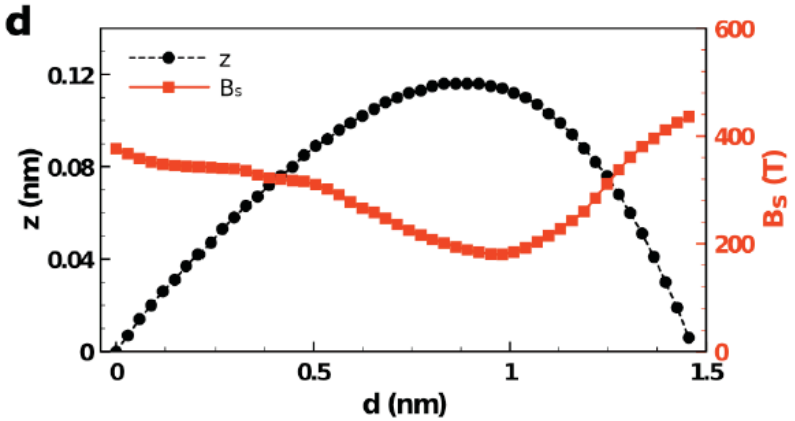
N. Levy, S.A. Burke, K.L. Meaker, M. Panlasigui, A. Zettl, F. Guinea, A.H. Castro Neto, and M.F. Crommie, unpublished.



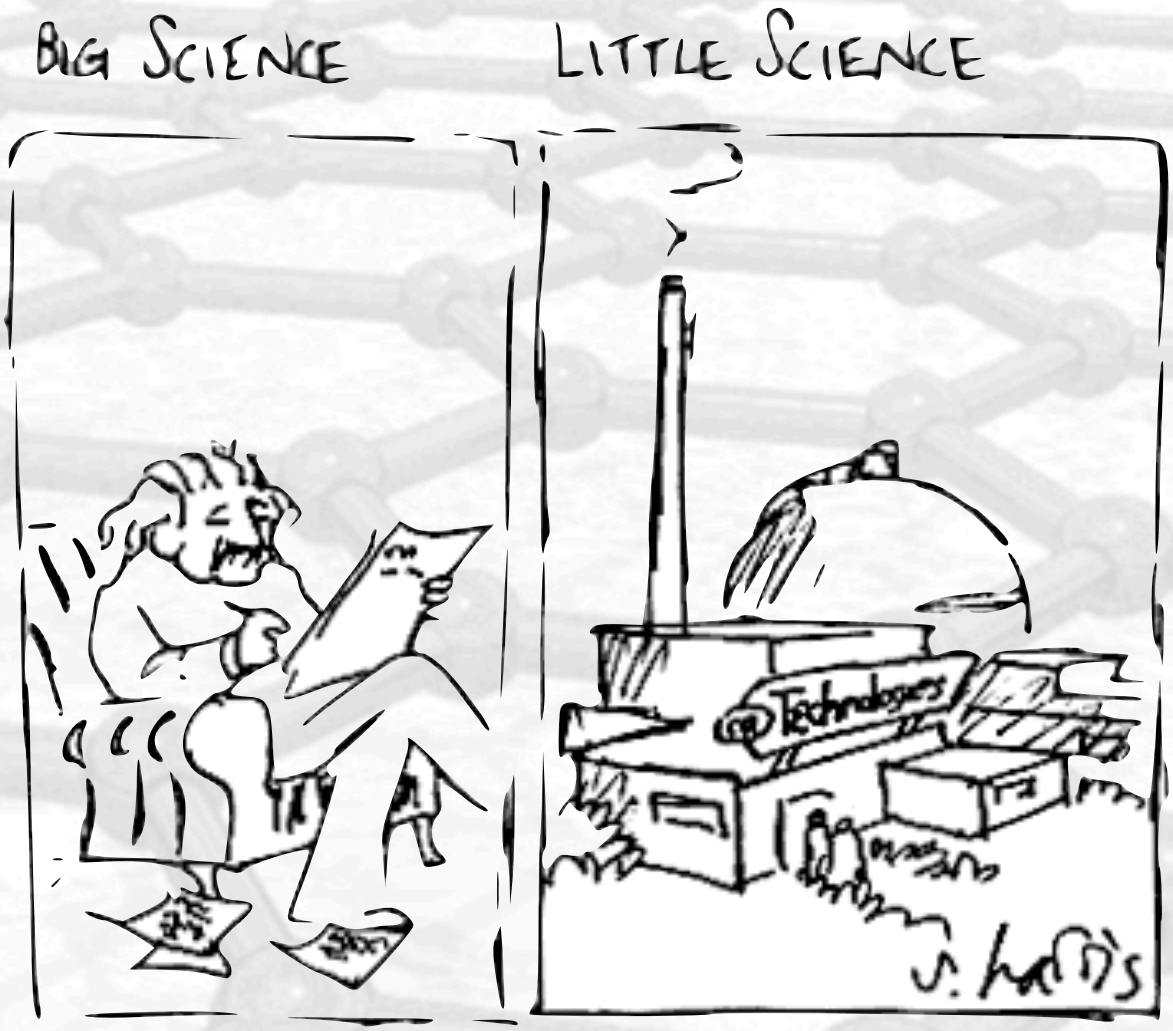


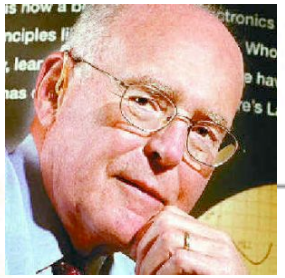






What about applications ?





Moore's Law Ending (Red Line): DeLayed products, DeLayed 45nm / 32 nm, Reduced Capex

10 BILLION TRANSISTORS PER CHIP

10 BILLION

1 BILLION

100 MILLION

10 MILLION

1 MILLION

100,000

10,000

2300

Future to 2018

2009

2015

2018

EVERY 18 MONTHS

$2300 \times 2^{0.6667 (Year - 1971)}$

ITANIUM 2 WITH 9-MB CACHE

ITANIUM 2

2006: MONTE-CITO, 1.7 BILLION

PENTIUM 4

ITANIUM

FUTURE PATH IN COLOR

TRANSISTORS/CHIP DOUBLING EVERY 2 YEARS (WORKED OUT WELL, BUT NOT MUCH LONGER.)

$N = 2300 \times 2^{0.5(Year - 1971)}$

PENTIUM III

PENTIUM II

PENTIUM

486

386

286

8086

8080

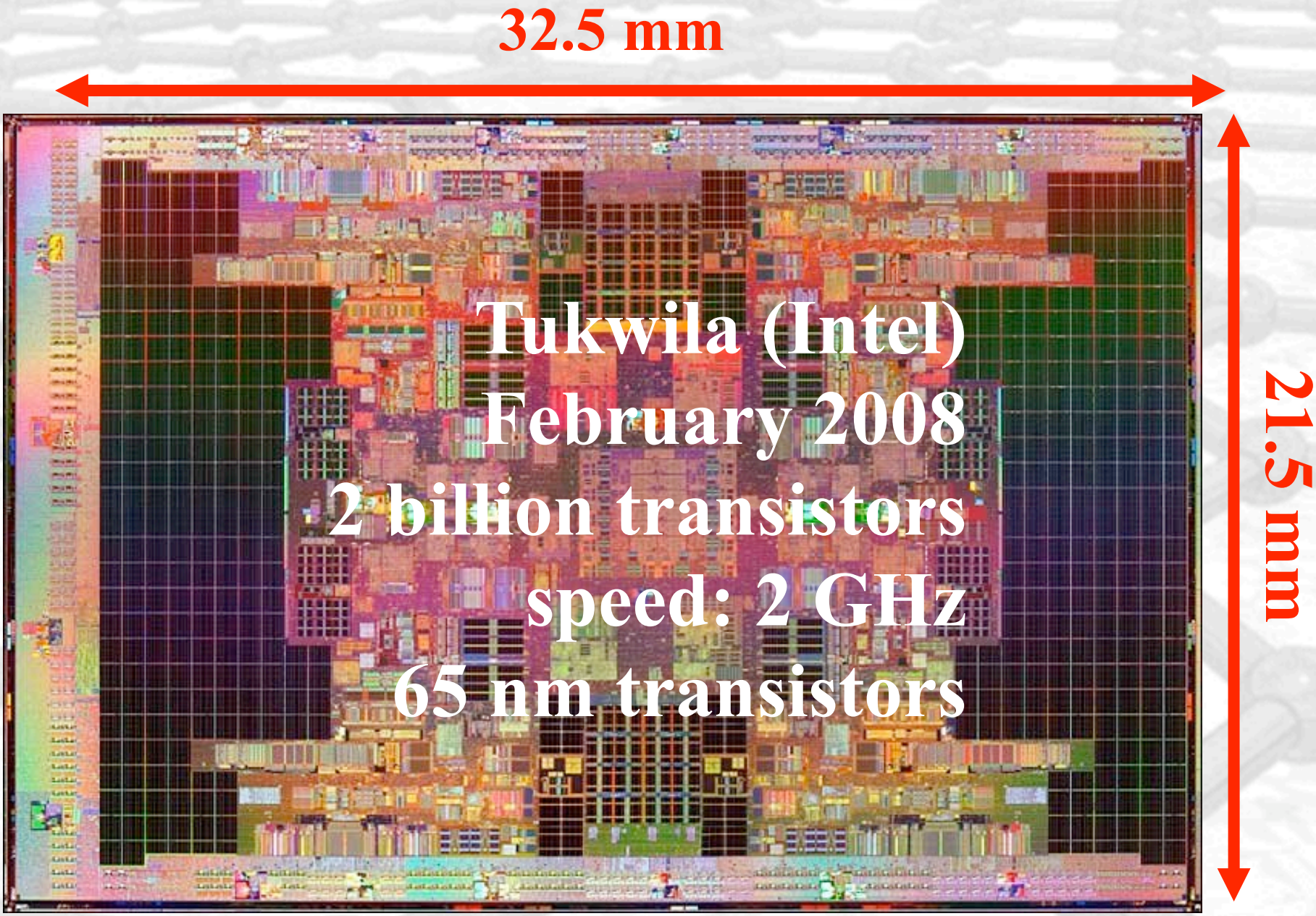
8008

4004

Based on logistic regression, asymptote at 6.25 billion.

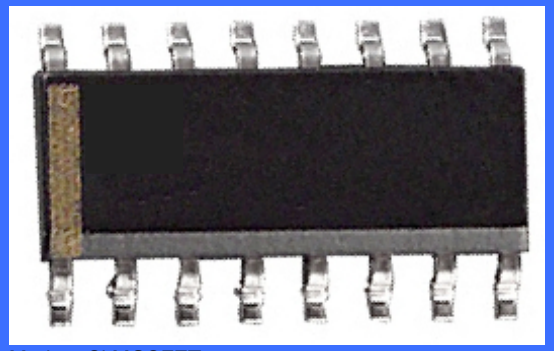
By Clayton Hallmark
Dedicated to
Professor Frederick E. Terman

1971 1980 Year 1990 2000 2004 2010 2015 2018

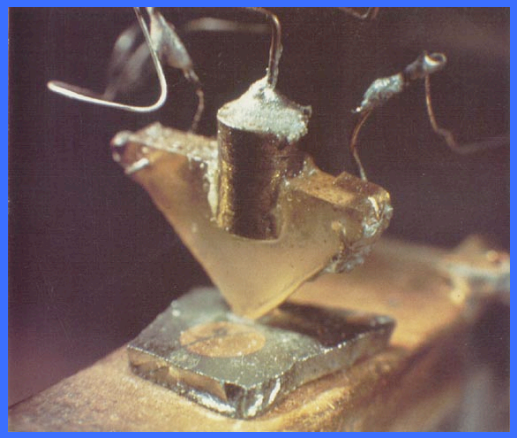

32.5 mm
21.5 mm
Tukwila (Intel)
February 2008
2 billion transistors
speed: 2 GHz
65 nm transistors

	carbon 6 C 12.011	
n	silicon 14 Si 28.086	p
	germanium 32 Ge 72.61	
	tin 50 Sn 118.71	
	lead 82 Pb 207.2	

? ? ? ?



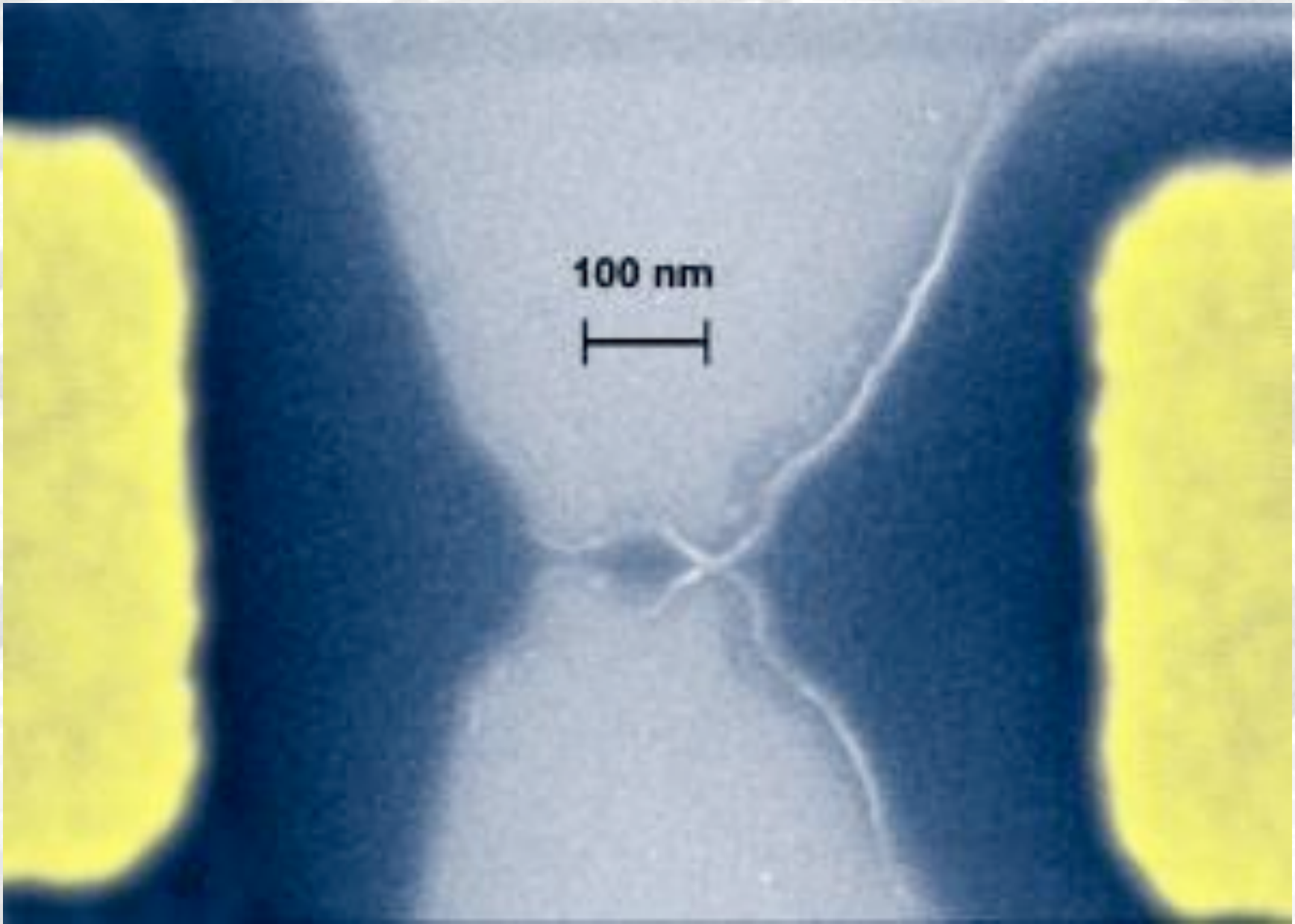
Modern Si MOSFET



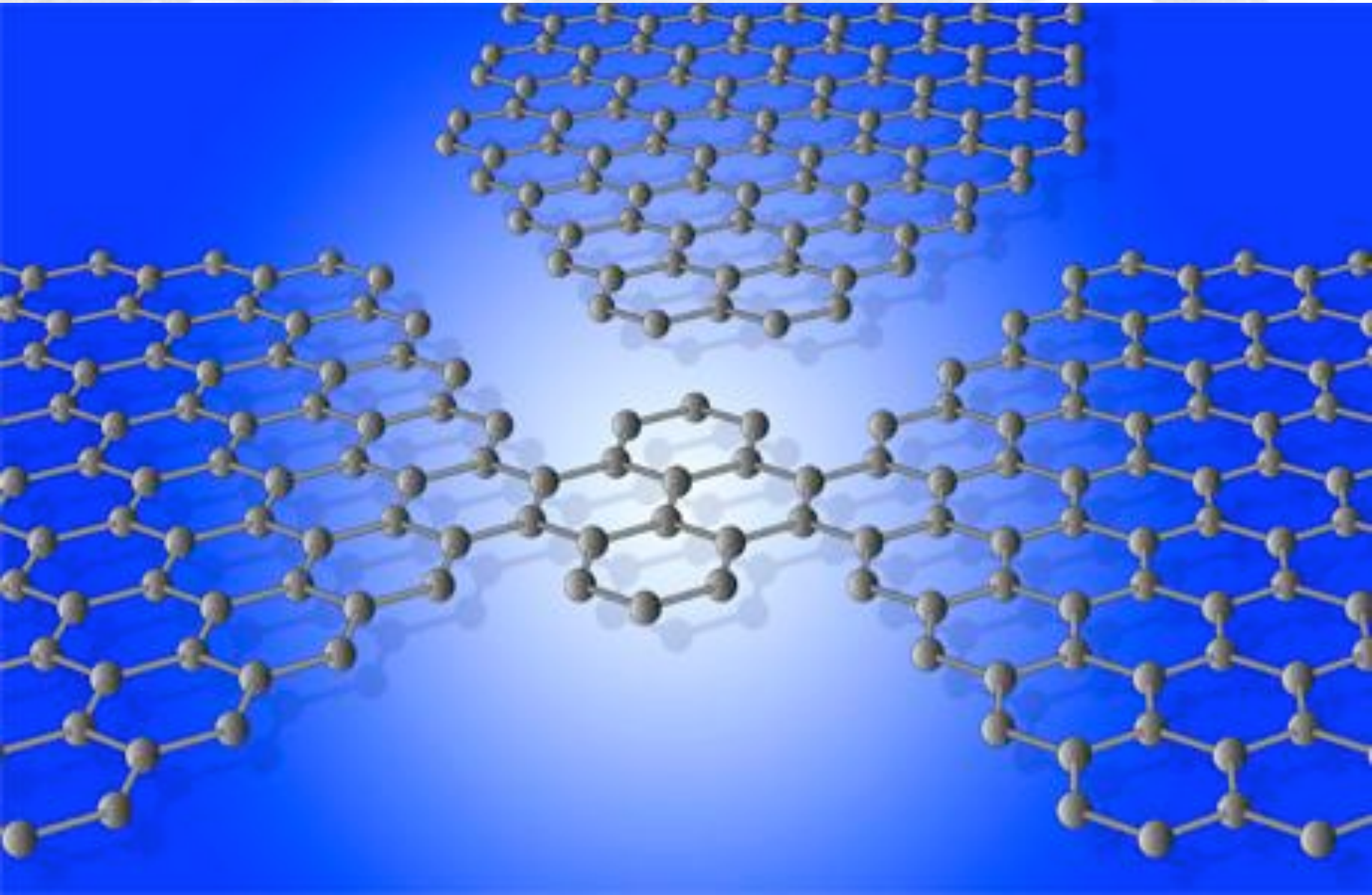
First Ge transistor

Graphene Quantum Dots

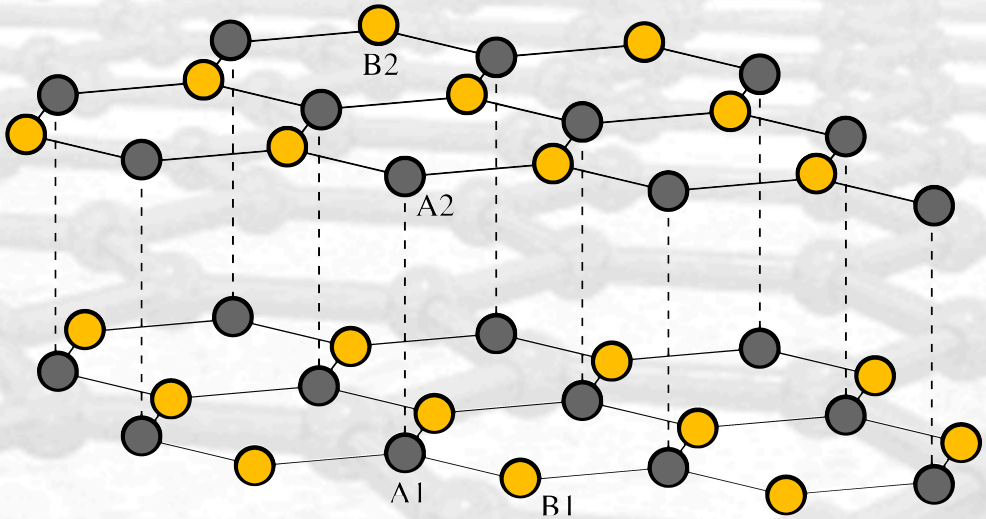
Graphene Quantum Dots



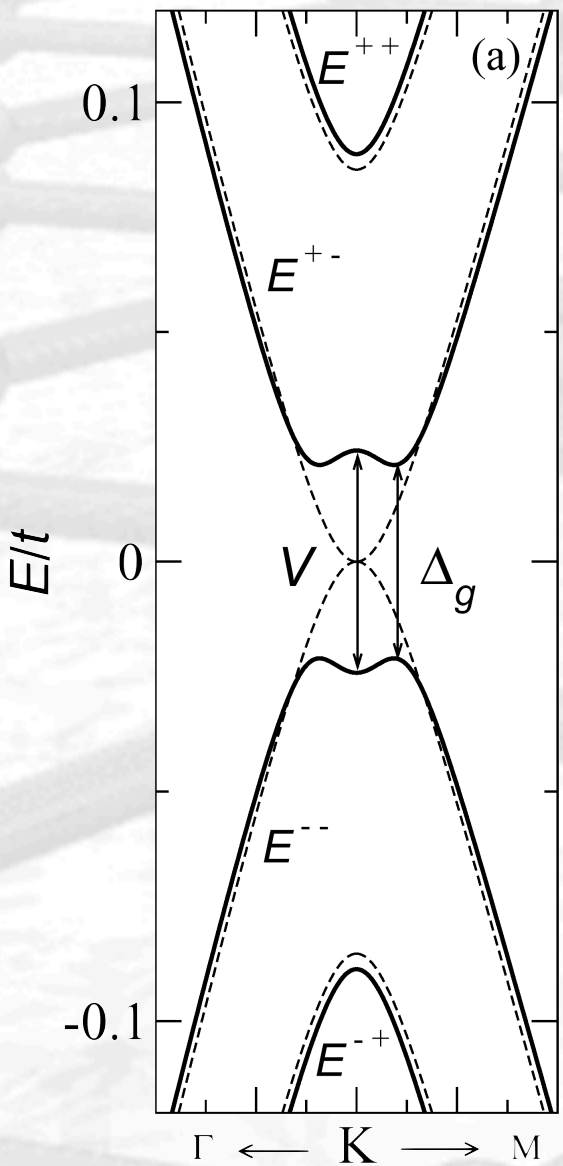
Miniaturization down to 1 nm : a few benzene rings

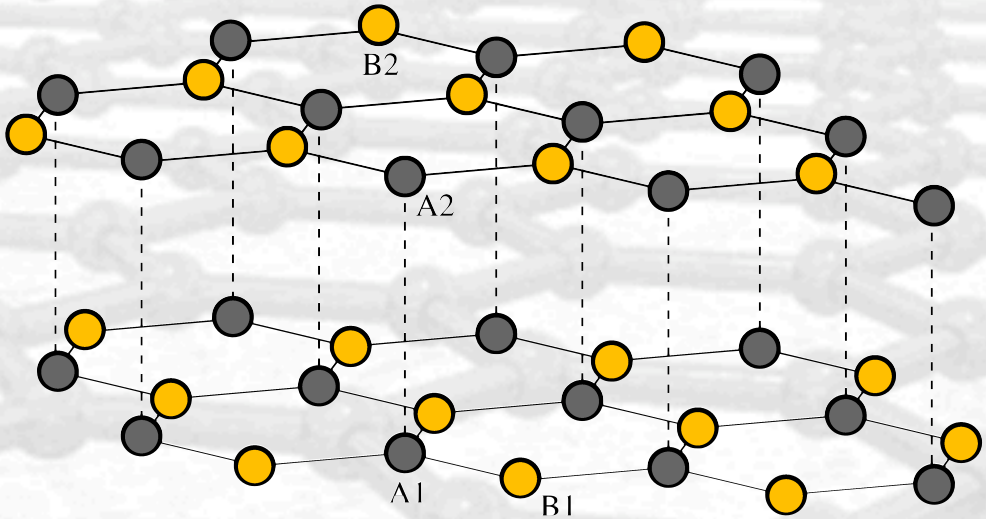


Graphene Bilayer

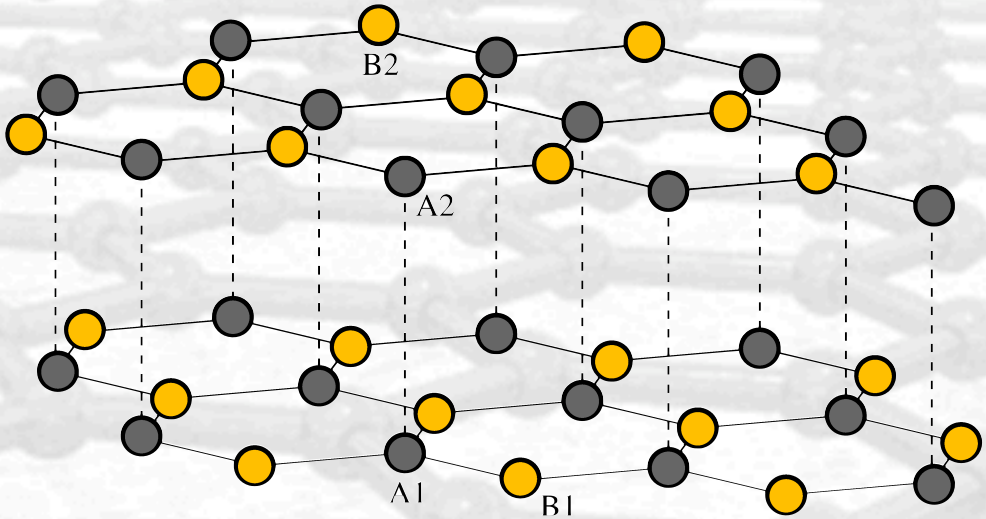


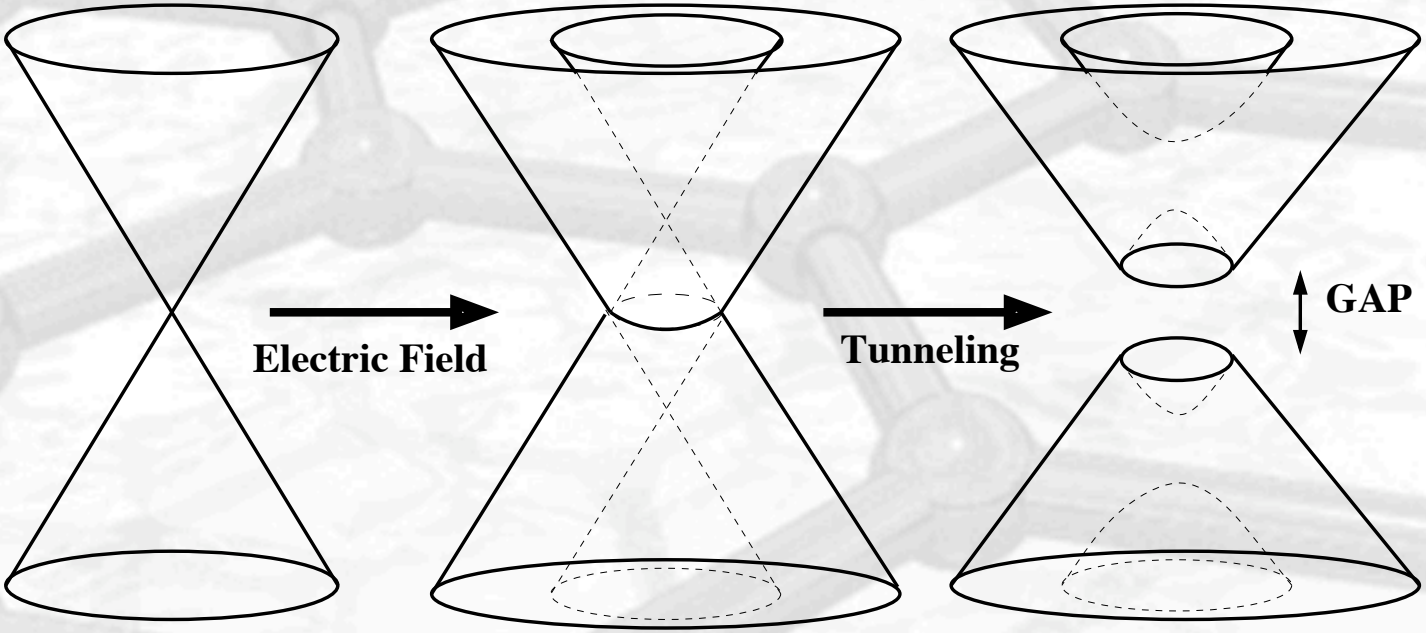
Graphene Bilayer





Graphene Bilayer

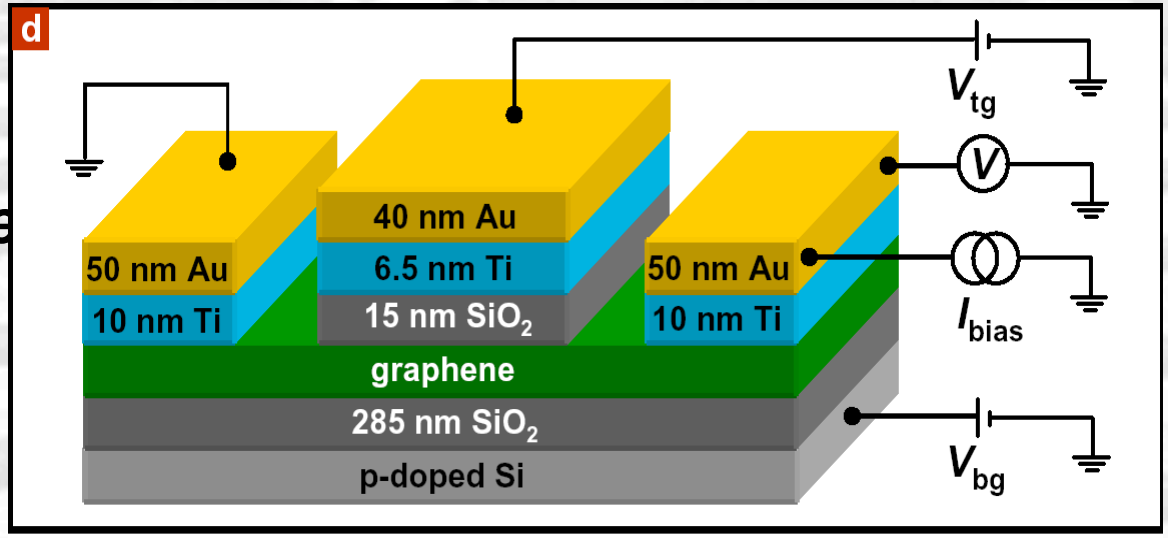


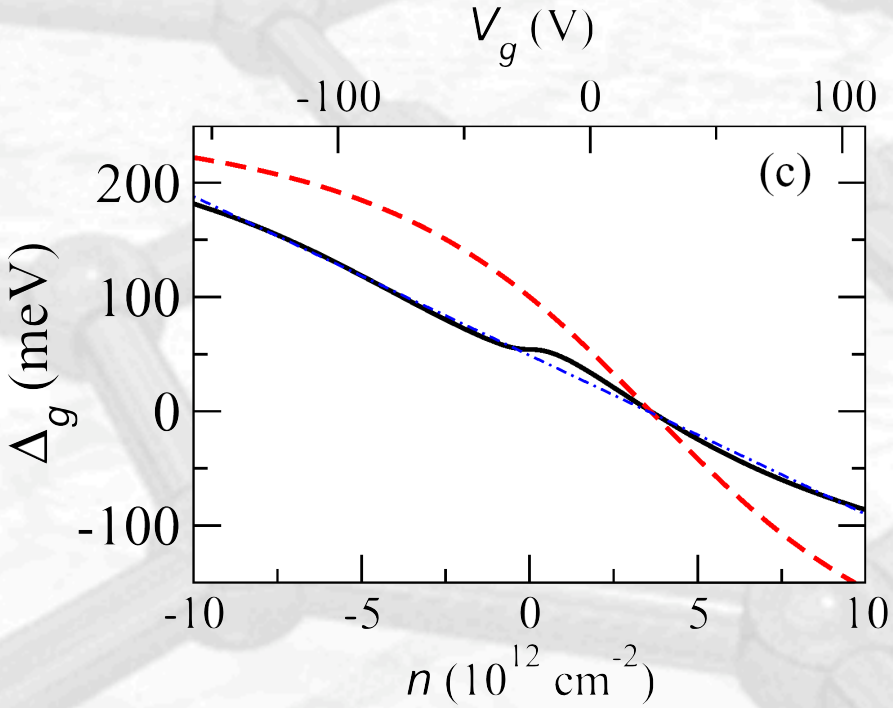


Dirac Cone

Graphene Bilayer

Semiconductor tunable by electric field effect





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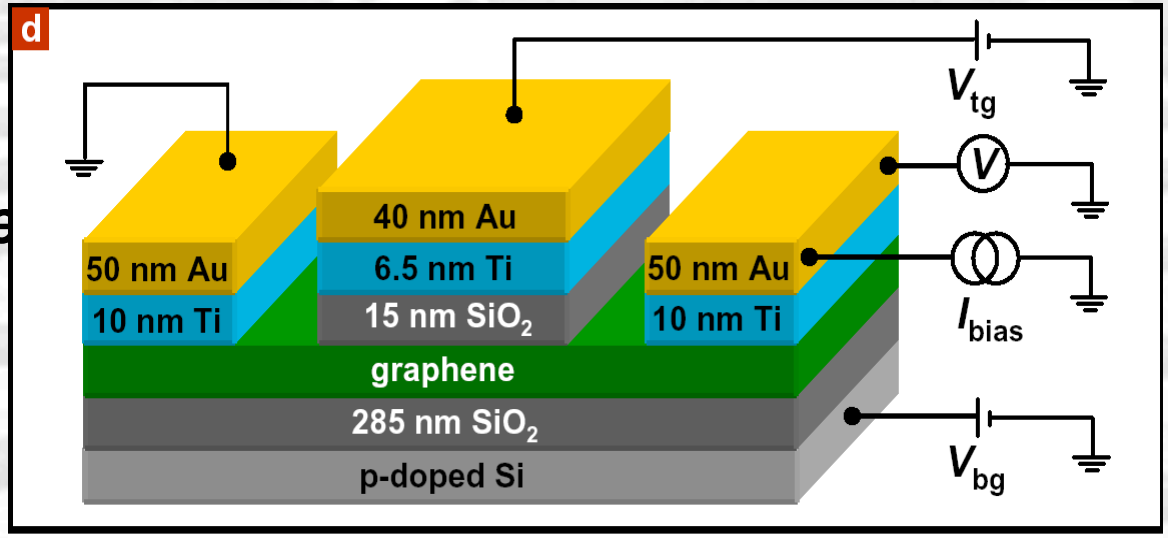
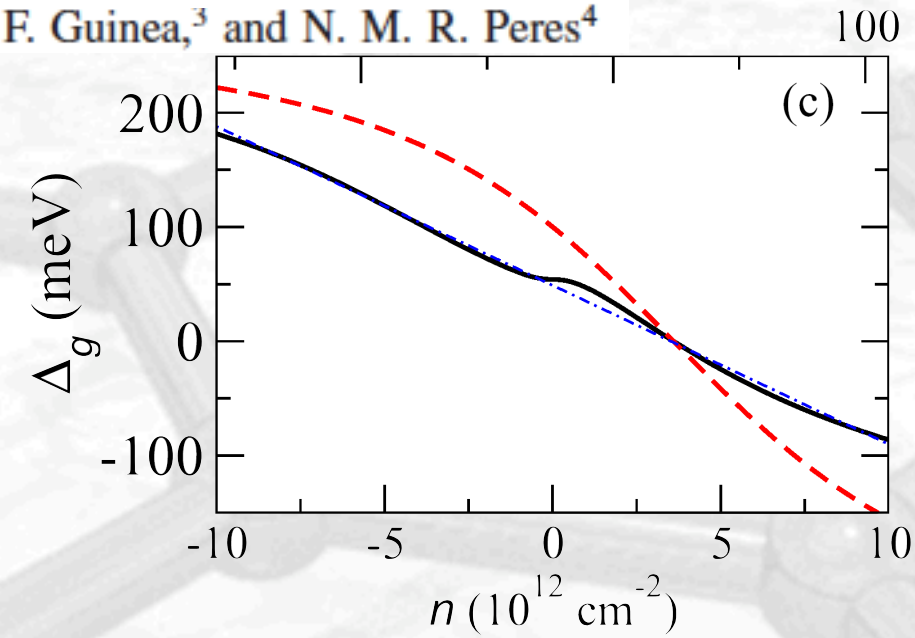


Electronic properties of bilayer and multilayer graphene

PHYSICAL REVIEW B 78, 045405 (2008)

Johan Nilsson,[1,2] A. H. Castro Neto,[1] F. Guinea,[3] and N. M. R. Peres[4]



Hype or Hope ?

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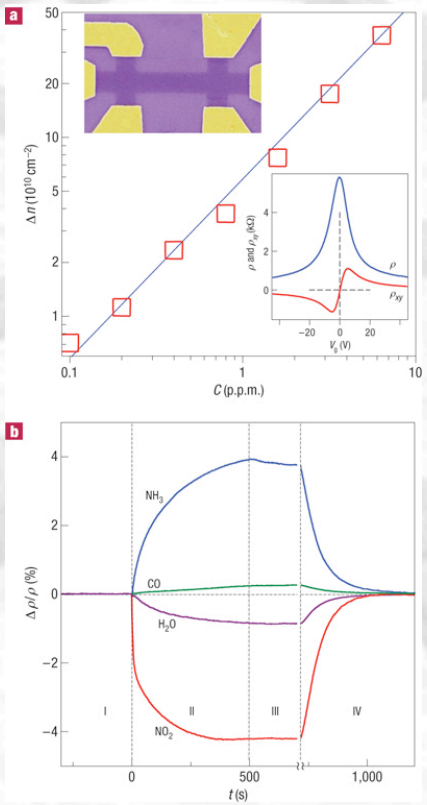
Detection of individual gas molecules adsorbed on graphene

F. Schedin, A. K. Geim, S. V. Morozov, E. W. Hill, P. Blake, M. I. Katsnelson & K. S. Novoselov

Nature Mater **6** (9): 652–655.



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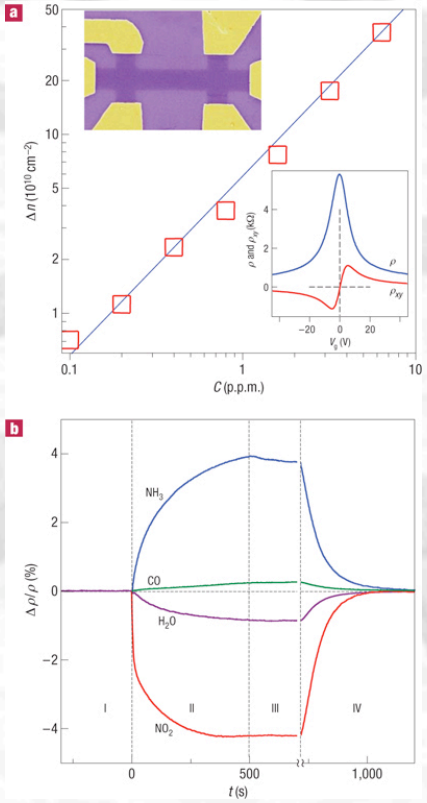
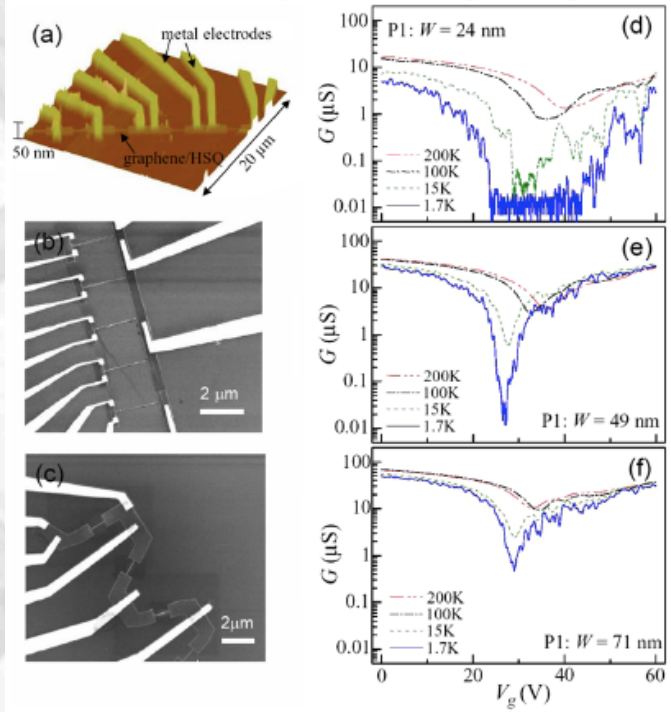


Energy Band-Gap Engineering of Graphene Nanoribbons

Melinda Y. Han,[1] Barbaros Özyilmaz,[2] Yuanbo Zhang,[2] and Philip Kim[2]

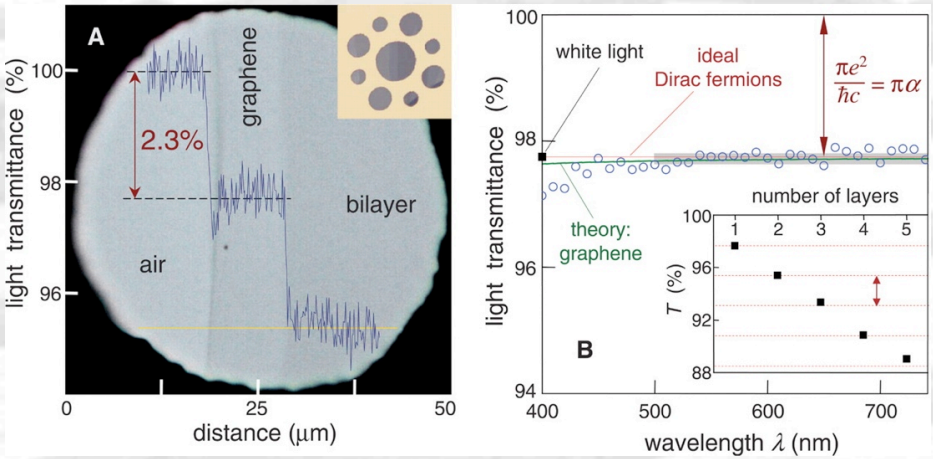
PRL 98, 206805 (2007)



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.



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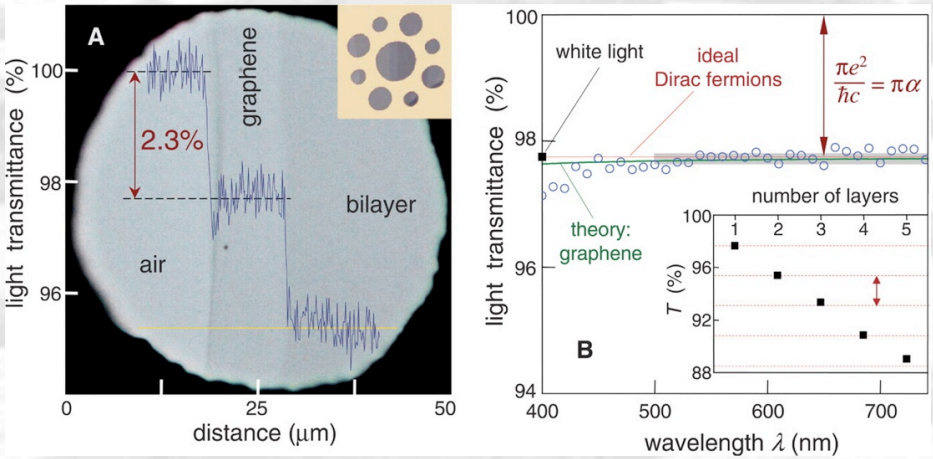
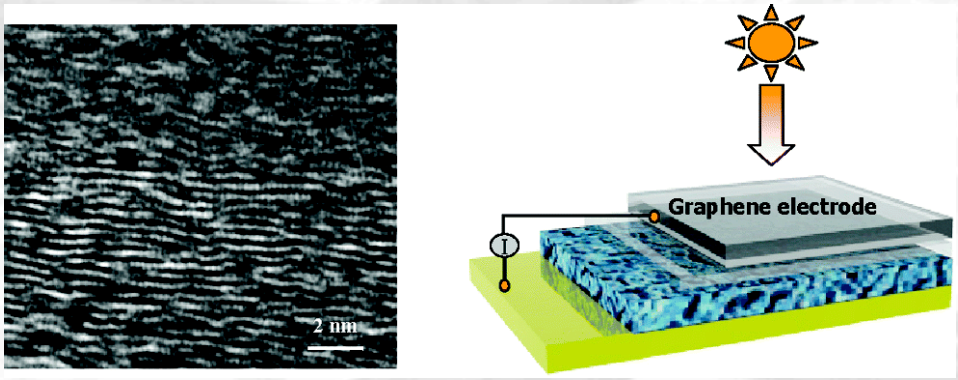


Transparent, Conductive Graphene Electrodes for Dye-Sensitized Solar Cells

Xuan Wang, Linjie Zhi, and Klaus Müllen

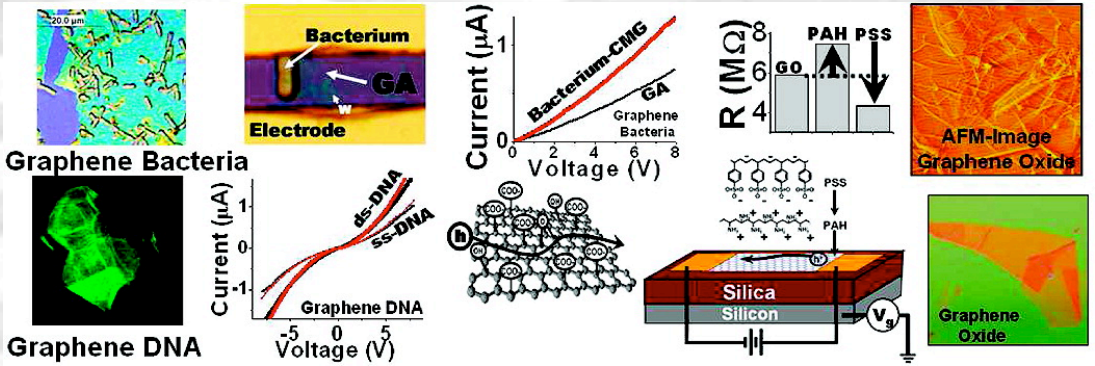
Nano Letters **8** (1): 323.



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



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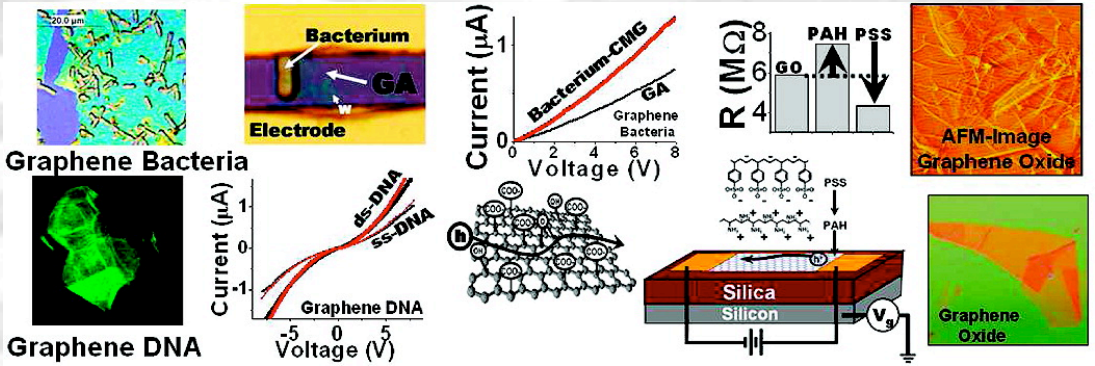
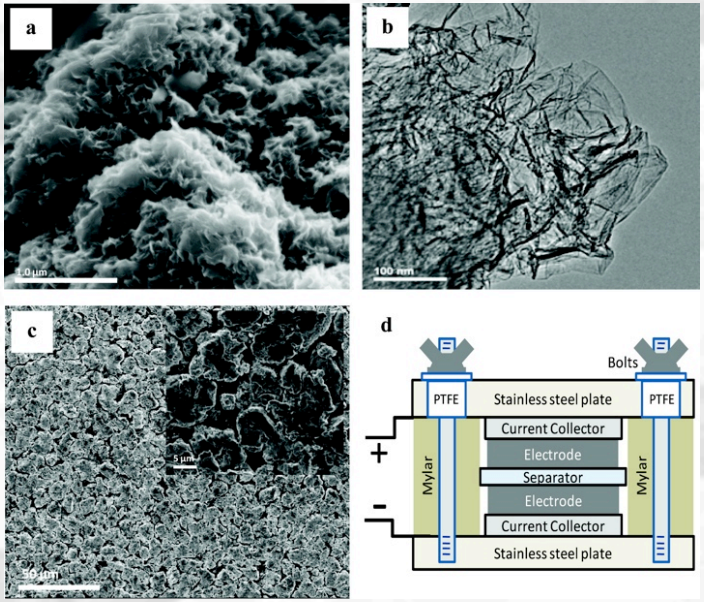


Graphene-Based Ultracapacitors

Meryl D. Stoller, Sungjin Park, Yanwu Zhu, Jinho An and Rodney S. Ruof

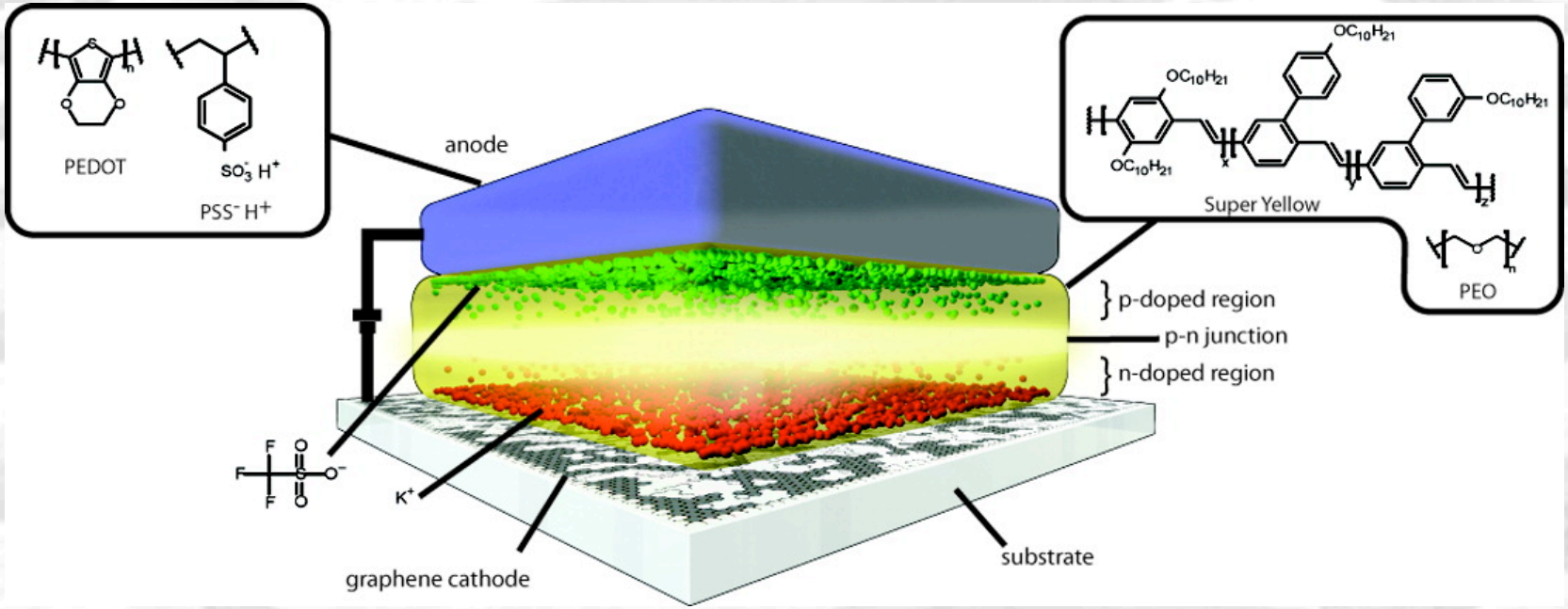
Nano Lett **8** (10): 3498.



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

ACS Nano, 2010, 4 (2), pp 637–642



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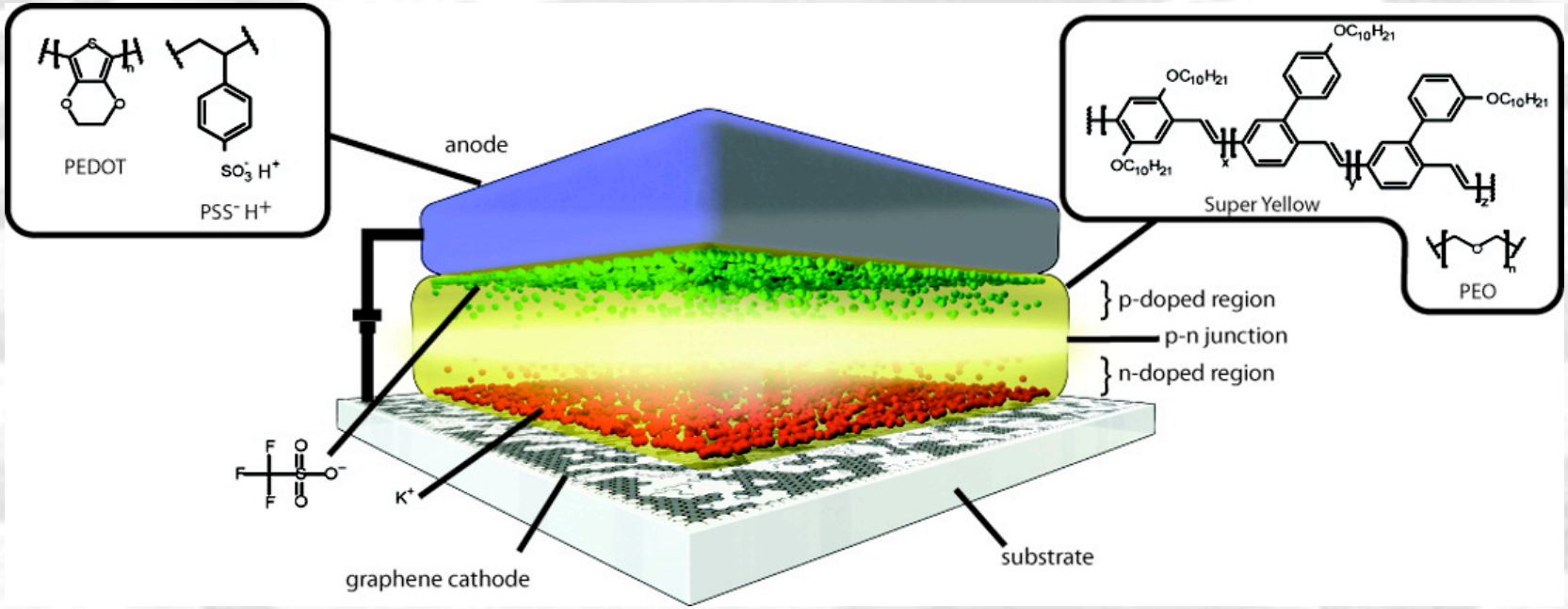
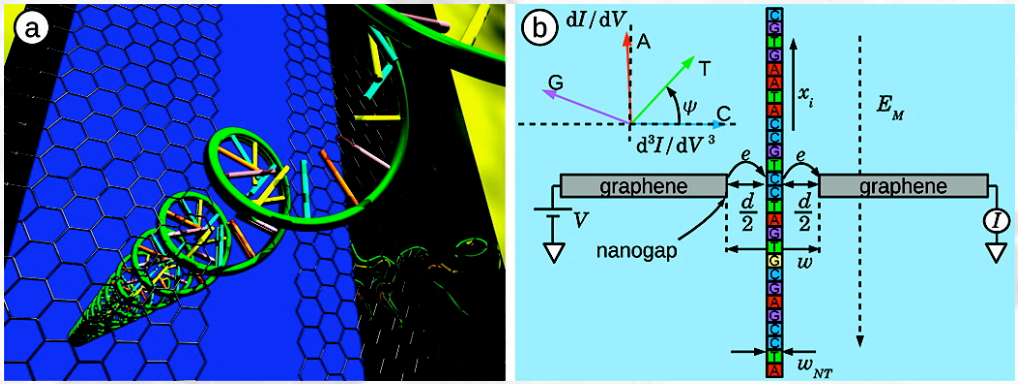


Rapid Sequencing of Individual DNA Molecules in Graphene Nanogaps

Henk W. Ch. Postma

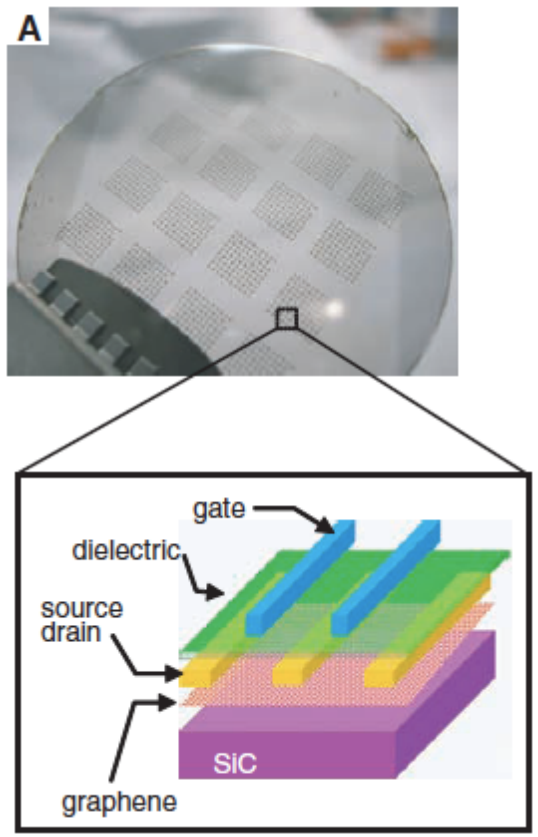
Nano Lett., 2010, 10 (2), pp 420–425

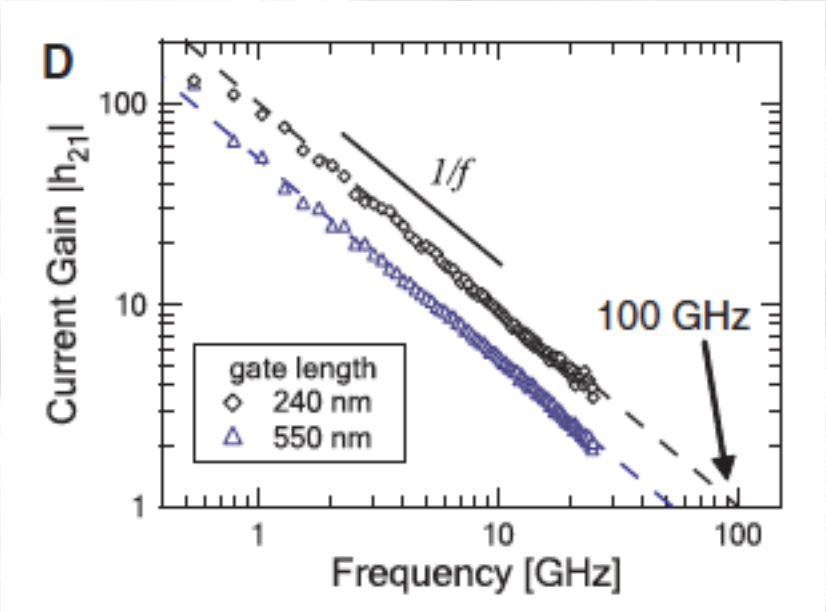


100-GHz Transistors from Wafer-Scale Epitaxial Graphene

Y.-M. Lin,* C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H.-Y. Chiu, A. Grill, Ph. Avouris*

5 FEBRUARY 2010 VOL 327 SCIENCE

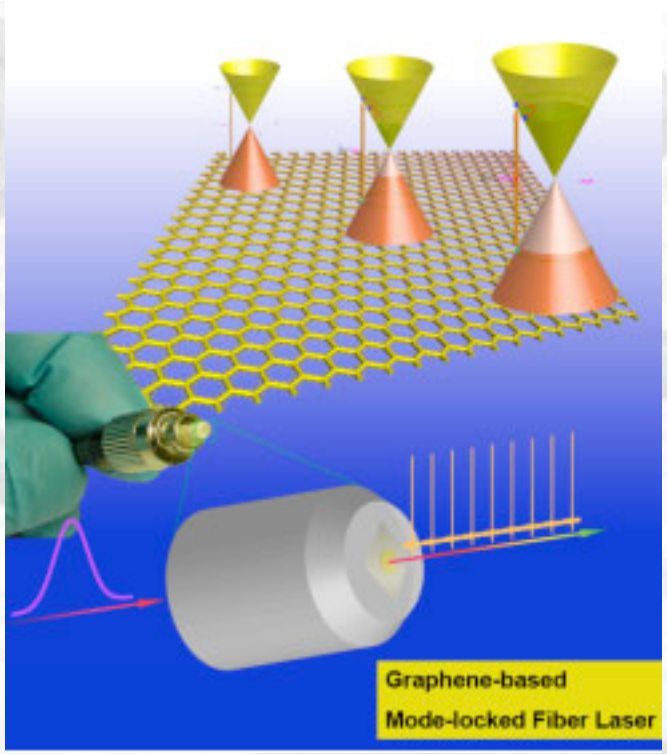




Atomic-Layer Graphene as a Saturable Absorber for Ultrafast Pulsed Lasers

Adv. Funct. Mater. **2009**, *19*, 3077–3083

By *Qiaoliang Bao, Han Zhang, Yu Wang, Zhenhua Ni, Yongli Yan, Ze Xiang Shen, Kian Ping Loh,** and *Ding Yuan Tang**



LASER FEST
CELEBRATING 50 YEARS OF LASER INNOVATION

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**

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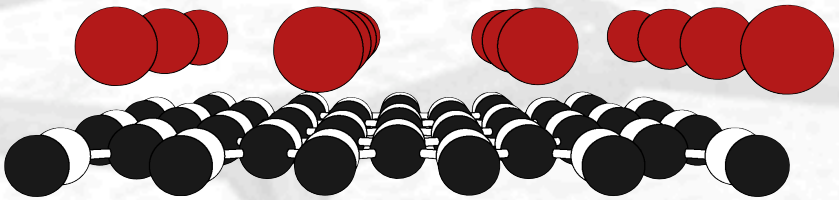

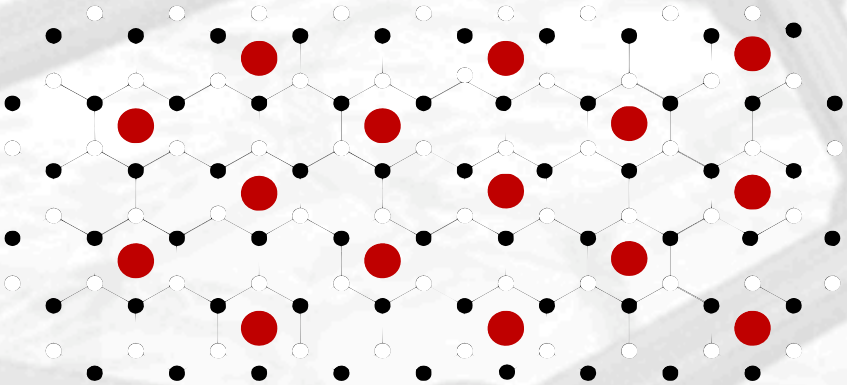

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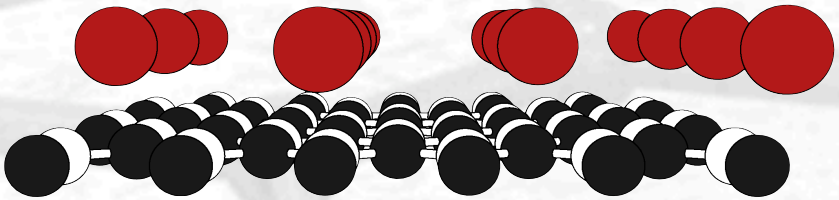

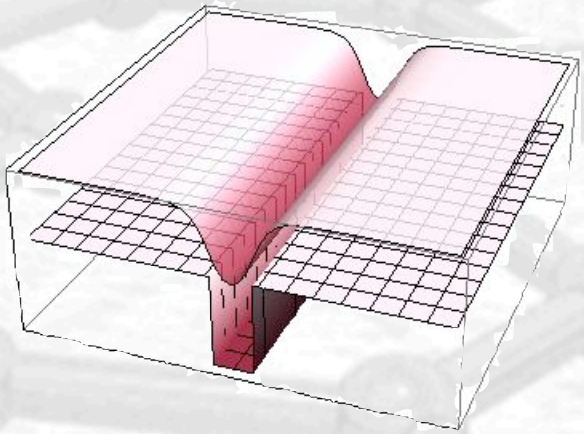

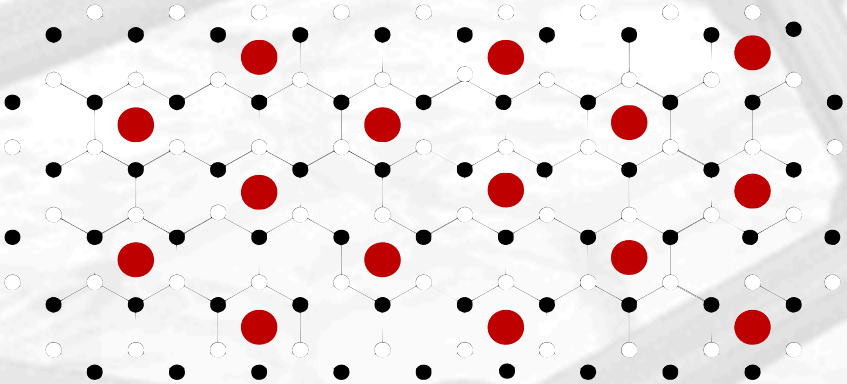

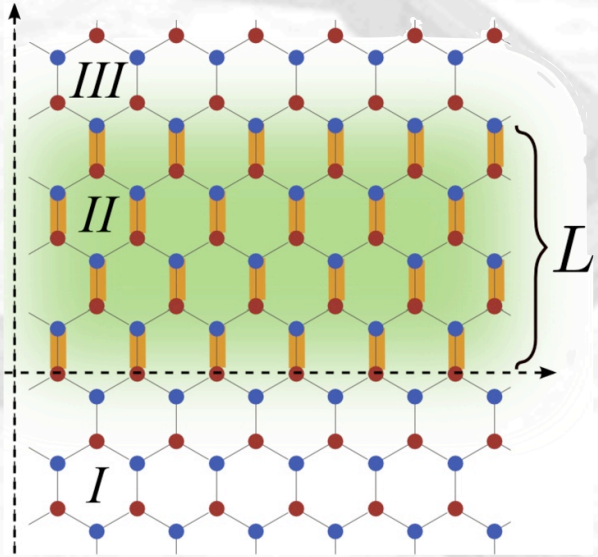

The rise of graphene… Much more to come ….