Graphene
The Noble Prize 2010

Qamar ul Wahab
NED University of Engineering and Technology, Karachi-Pakistan
and
Linköping University, Sweden

Linköping University

Linköping – Norrköping
Sweden's fourth "metropolitan" region

Linköping

135,000 inhabitants

Norrköping

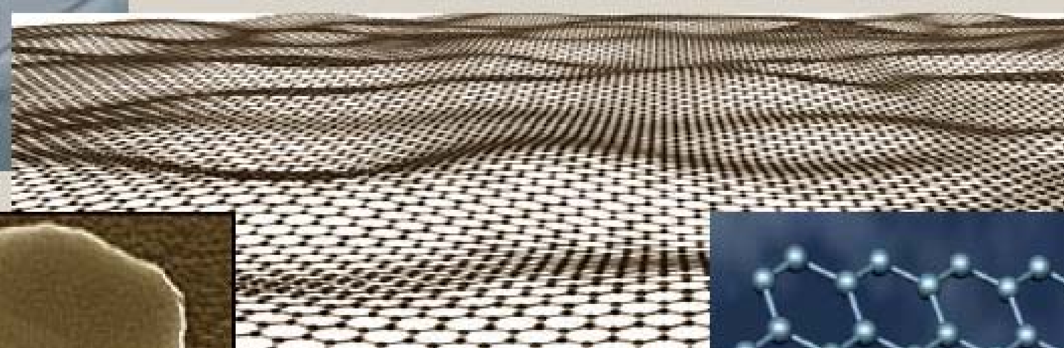
125,000 inhabitants

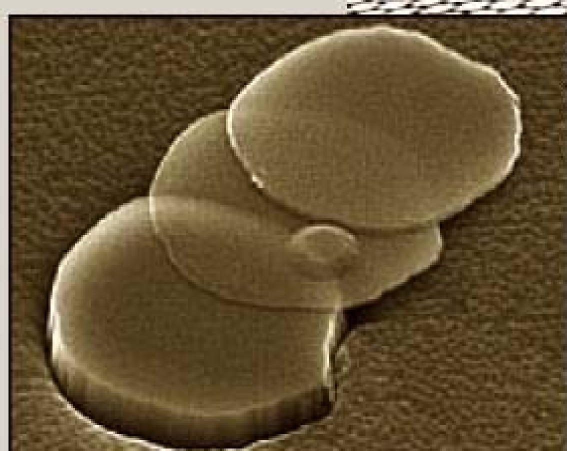
Properties

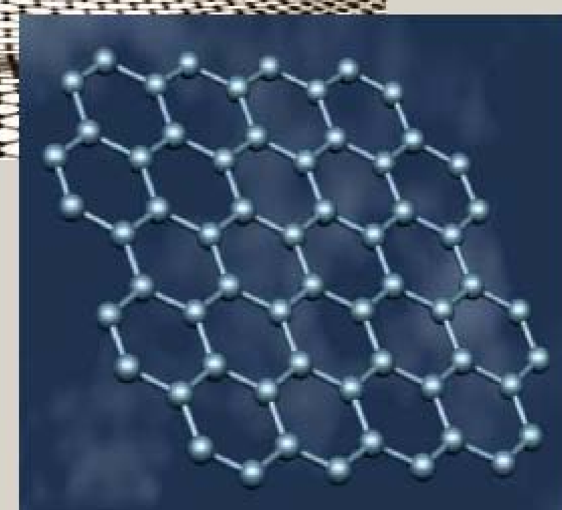
- What is Graphene ?
- **Material of the future**
- **Amazing physical properties**

GRAPHENE

the first 2D crystal lattice







Noble Prize 2010

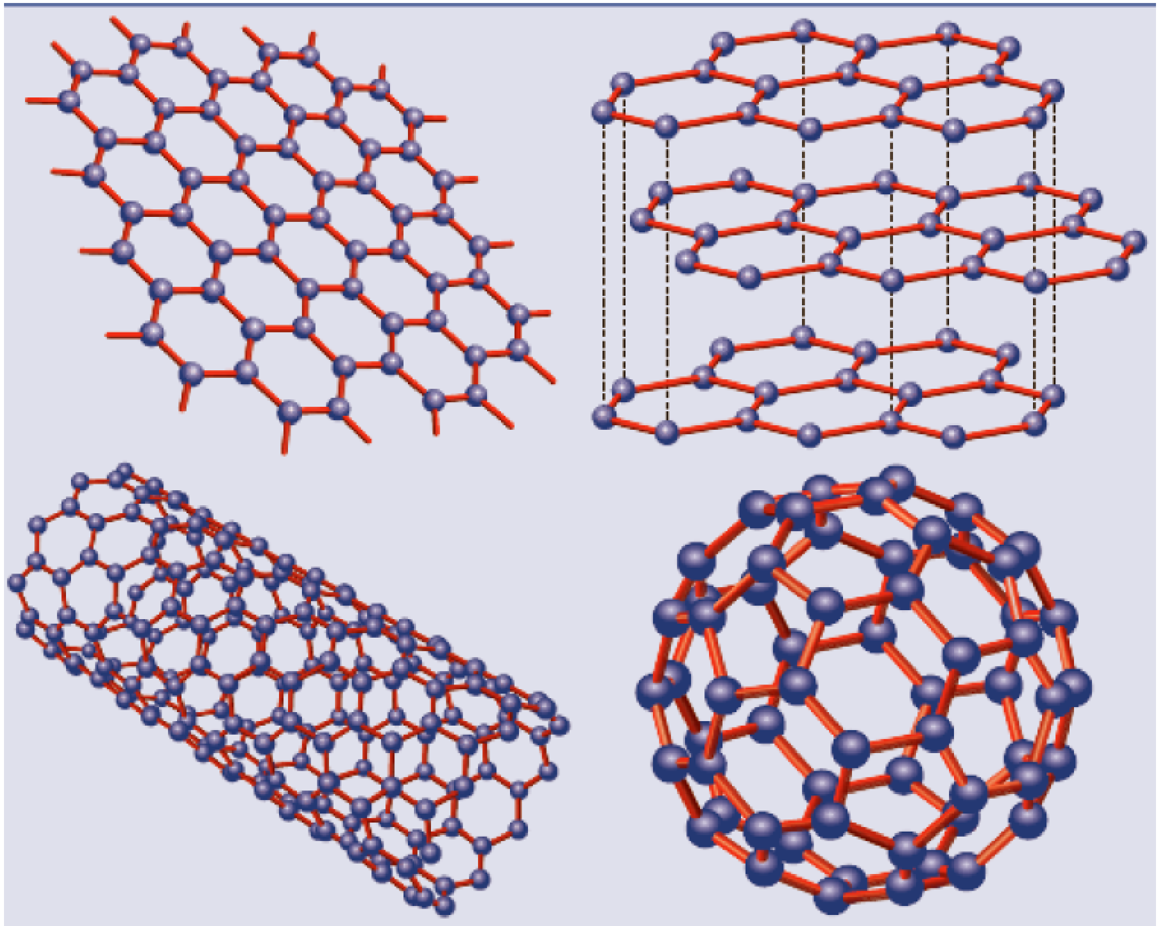
For groundbreaking experiments regarding the two-dimensional material graphene

Andre Geim
Born: 1958, Sochi, Russia
Affiliation at the time of the award: University of Manchester, Manchester, United Kingdom

Konstantin Novoselov
Born: 1974, Nizhny Tagil, Russia
Affiliation at the time of the award: University of Manchester, Manchester, United Kingdom

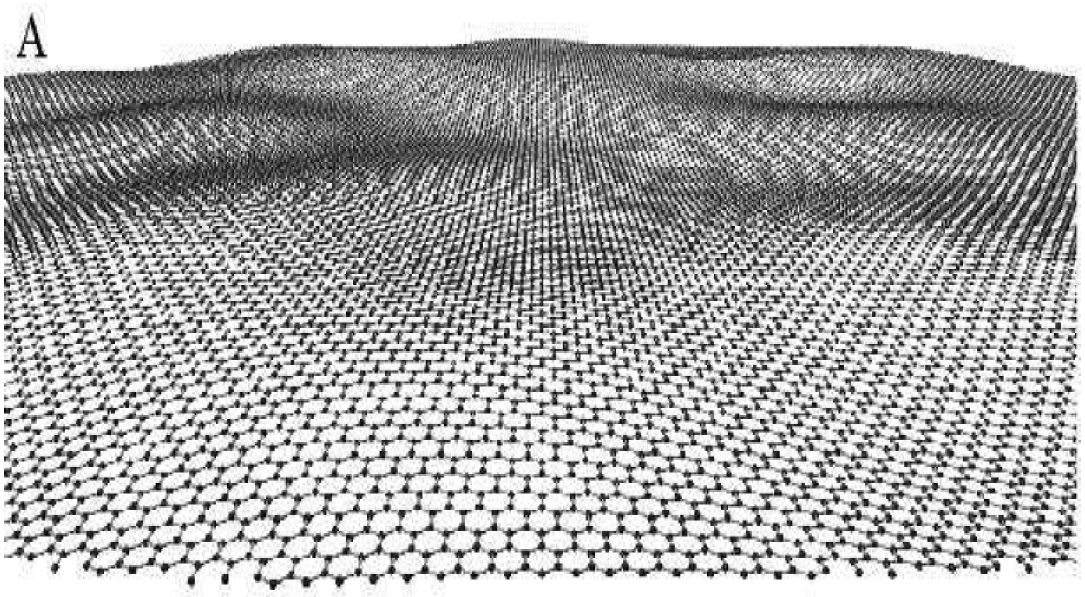
What is Graphene

"**Graphene** is the name given to a flat monolayer of carbon atoms tightly packed into **a two-dimensional (2D) honeycomb lattice**, and is a basic building block for graphitic materials of all other dimensionalities. It can be wrapped up into 0D fullerenes, rolled into 1D nanotubes or stacked into 3D graphite." [*Nature Mat. 6, 2007*].



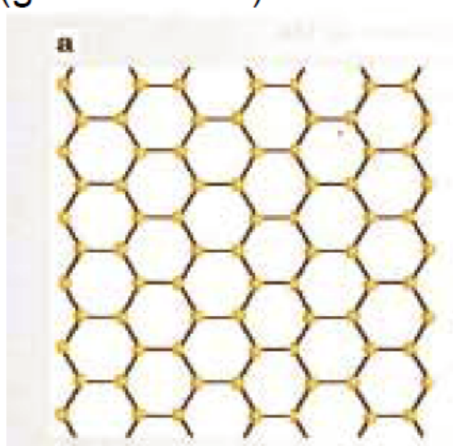
What is Graphene !

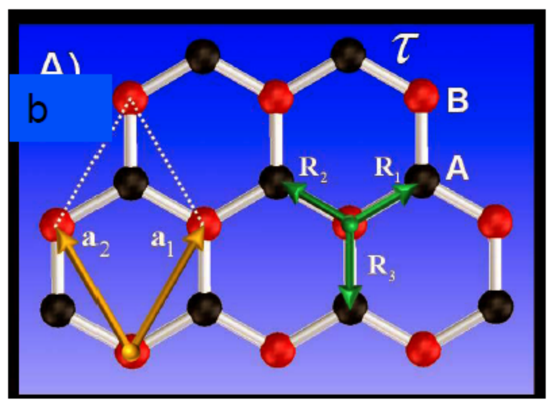
- Graphene is one-atom-thick planar sheets of sp2-bonded carbon atoms
- densely packed in a honeycomb crystal lattice.



Crystal structure of Graphene

• (a) : covalently sp^2 bounded atoms in a 2D honeycomb structure of C atoms => strong bonds with the neighbors; one unbound electron left => conductivity.
• The basic lattice structure of graphene (b) made up of two interpenetrating hexagonal carbon sublattices, labeled **A** (black spheres) and **B** (red spheres), forming a honeycomb pattern. The unit cell (white dotted diamond) contains two atoms (A and B), and is defined by the lattice vectors $\mathbf{a_1}$ and $\mathbf{a_2}$ (gold arrows). The distance between honeycombs, $a=a_1=a_2$ is 2.46 Å. Nearest-neighborhood carbon atoms are defined by translation vectors Rj (green arrows).





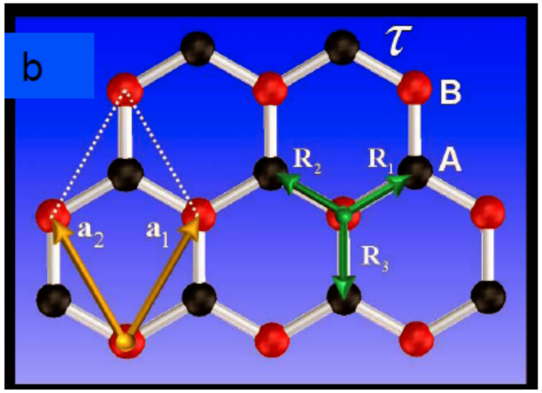
A-B distance = 1.42Å

The almost perfect web is only one atom thick. It consists of carbon atoms joined together in a hexagonal pattern similar to chicken wire.

Bonding and crystal structure

• The bonds between the **A** and **B** carbon atoms have a strong interatomic coupling, τ ~-3.0 eV. The large value of τ is the reason for the strength and robustness of the in-plane sp2-hybridized bonds.

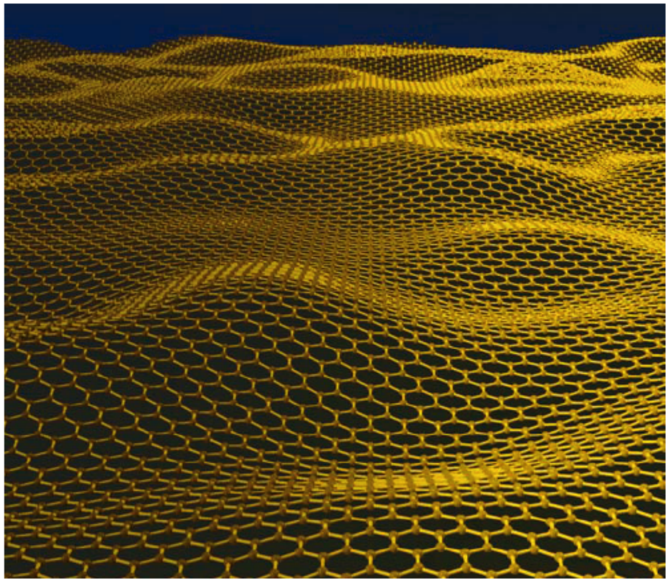
• Since the **A** and **B** atoms are identical carbon atoms, the graphene lattice has what is called **sublattice** symmetry. This sublattice symmetry influences the electronic structure of graphene greatly. For example, it is well known that the crystal structure of boron nitride has a similar honeycomb lattice to graphene. However, since there are two different atoms in the lattice (no sublattice symmetry), the electronic properties are very different from that of graphene.



A-B distance = 1.42Å

Why 2D Graphene is stable?

"It can be argued that the obtained 2D crystallites are quenched in a metastable state because they are extracted from 3D materials, whereas their small size (<<1 mm) and strong interatomic bonds ensure that thermal fluctuations cannot lead to the generation of dislocations or other crystal defects even at elevated temperature." ***[Nature Mat. 6, 2007]***



- A complementary viewpoint is that the extracted 2D crystals become intrinsically stable by gentle crumpling in the third dimension. Such 3D warping (observed on a lateral scale of ≈10 nm) leads to a gain in elastic energy but suppresses thermal vibrations (anomalously large in 2D), which above a certain temperature can minimize the total free energy. ***[Nature 446, 2007].***

[Jannik Meyer, Science vol 324, 15 May 2009]

Future Applications

Let us see this movie by Samsung
You can find on YouTube

How to Grow Graphene for Electronic Applications

Graphene Growth

Large-area synthesis of high-quality and uniform graphene films on copper foils
Li, W Cai, J An, S Kim, J Nah, D Yang… - Science, 2009
Graphene films transferred onto a SiO_2/**Si** substrate and a glass plate, respectively. **...**

Large-scale pattern growth of graphene films for stretchable transparent electrodes
KS Kim, Y Zhao, H Jang, SY Lee, JM Kim, KS Kim… - Nature, 2009

Large area, few-layer graphene films on arbitrary substrates by chemical vapor deposition
Reina, X Jia, J Ho, D Nezich, H Son… - Nano letters, 2008

Homogeneous large-area graphene layer growth on 6H-SiC (0001)
C Virojanadara, M Syväjarvi, R Yakimova… - Physical Review B, 2008

Thermodynamics and kinetics of graphene growth on SiC (0001)
RM Tromp… - Physical review letters, 2009

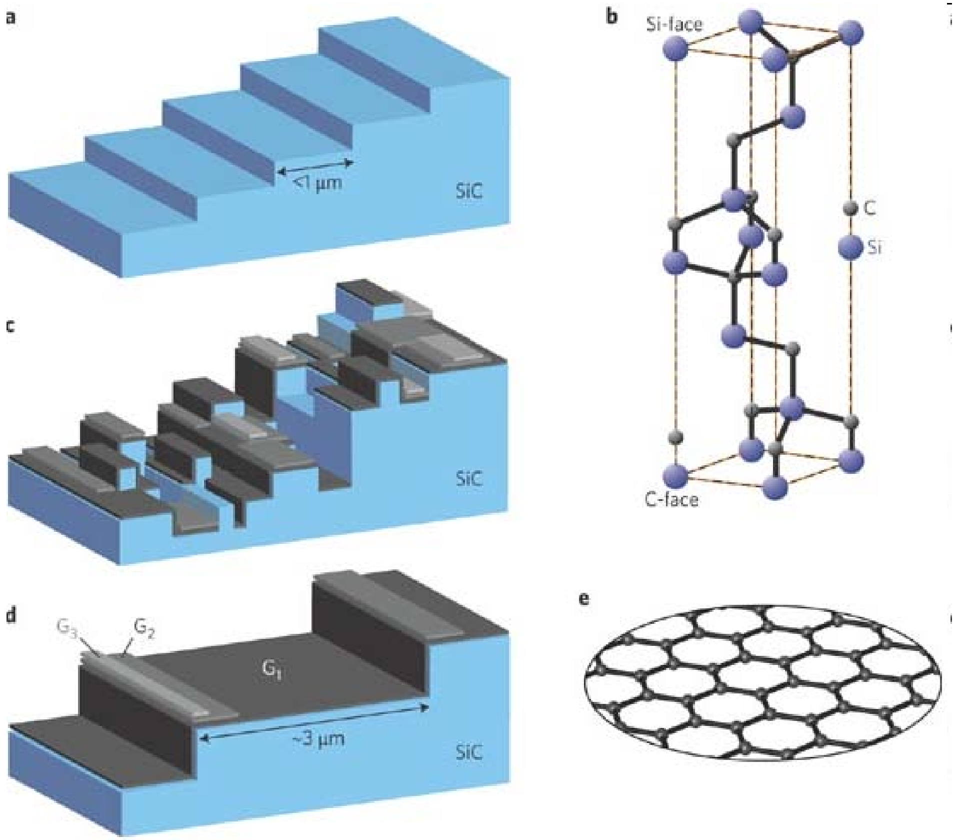
The growth and morphology of epitaxial multilayer graphene
J Hass, WA Heer… - Journal of Physics: Condensed …, 2008

Towards wafer-size graphene layers by atmospheric pressure graphitization of silicon carbide
KV Emtsev, A Bostwick, K Horn, J Jobst… - Nature Materials, 2009

Evidence of structural strain in epitaxial graphene layers on 6H-SiC (0001)
N Ferralis, R Maboudian… - Physical review letters, 2008

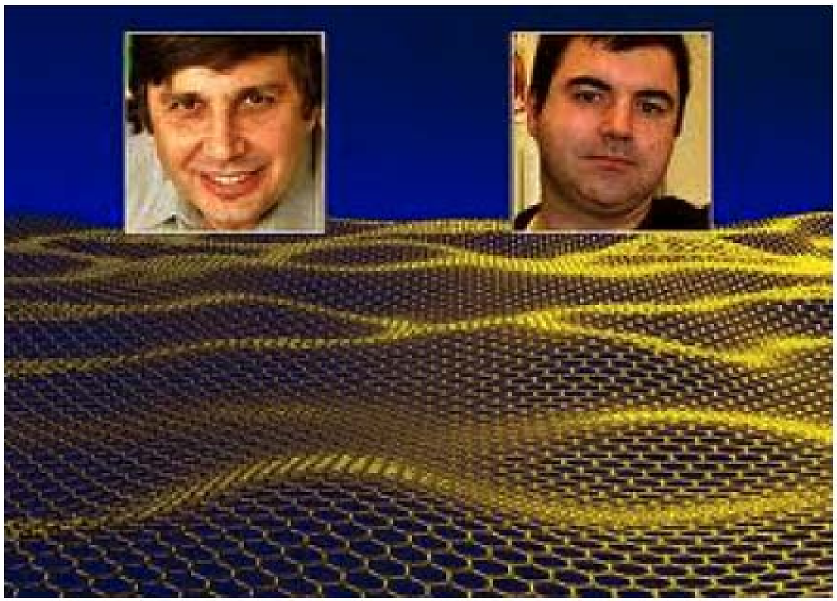
Graphene on SiC

a, SiC starting surface with a staircase of flat terraces and atomic steps.
b, Unit cell of 6H-SiC. **c**, Schematic morphology of vacuum-graphitized SiC.
d, Morphology obtained in high-pressure argon.
The surface termination is predominantly monolayer graphene, G1
(**e**), with narrow stripes of bilayer (G2) and trilayer (G3) graphene near the upper edge of the substrate steps.

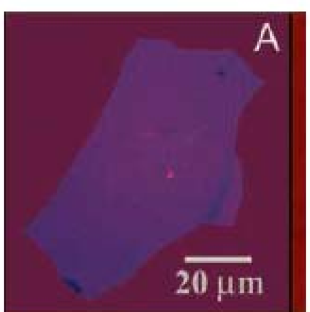


How Graphene was produced

About the Laureates



They have drawn their success by a simple graphitic pencil.



"Seeing is believing"
[Japanese wisdom]

Noble prize 2010, Experiment

Nobel Prize in Physics 2010

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

GRAPHENE – the perfect atomic structure

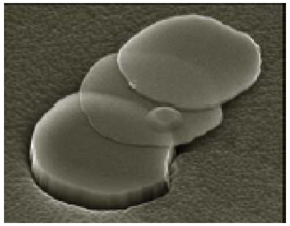
It just waited to be discovered

"Graphite is a basic material found in nature. When taken apart graphite sheets become graphene."

[Information for the public, HTTP://KVA.SE]

It has not been "visible" until 2004

- The new two-dimensional crystalline material discovered by K. Novoselov and A. Geim (University of Manchester, UK) in 2004.
- Graphene was first obtained by delicately cleaving a sample of graphite with sticky tape => suspended graphene, a free standing 2D crystal.
- Peeling away thin graphite layers => obtained single atomic graphene sheets.



[Phys. World, 11, 2006]

How Graphene can be produced

- Exfoliated graphite, either mechanically or in a liquid-phase solution
- Chemical intercalation
- Chemical synthesis, e.g. passing ethanol into an argon plasma
- Sublimation of Si from SiC wafers
- Chemical vapor deposition
- ....

How you can produce Graphene

- Watch this movie

Optical visibility

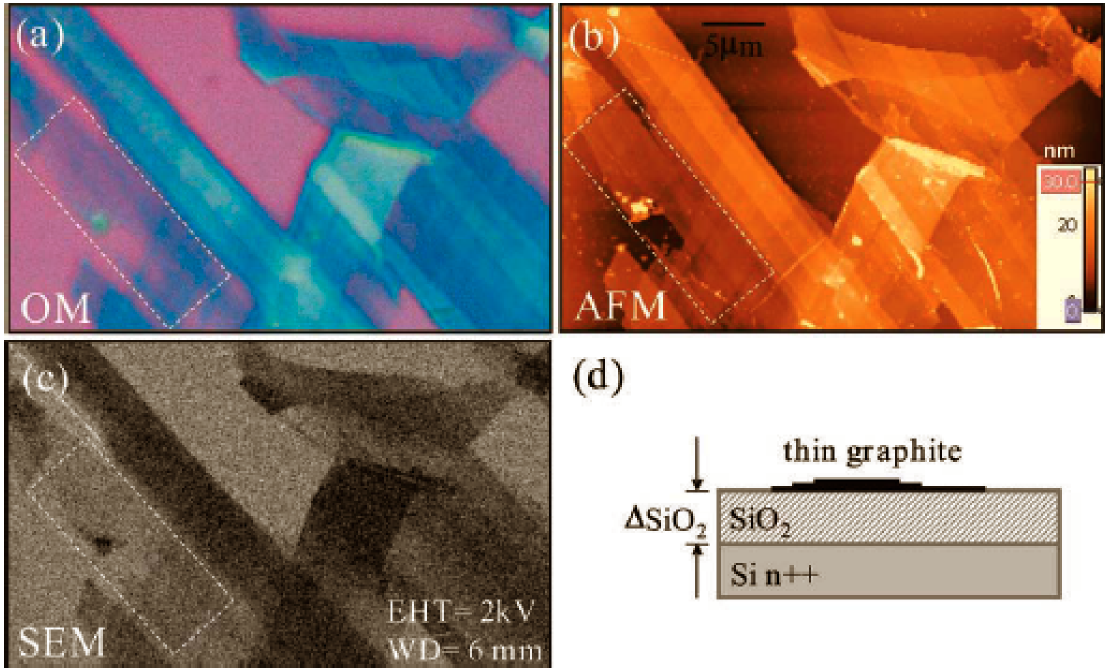
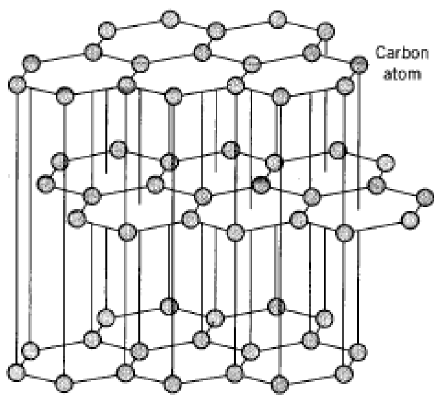


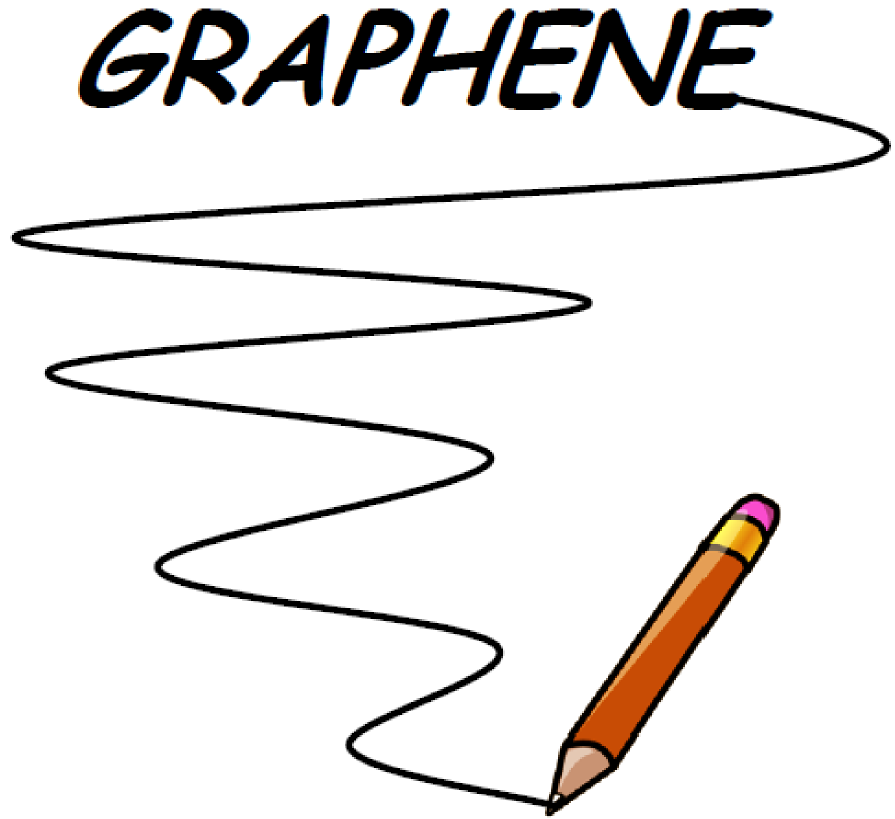
Image of big graphite flake containing regions of many different thicknesses. The pictures were taken using an optical microscope (a), an atomic force microscope (b), and a scanning electron microscope (c). A ultrathin graphite region (thickness below 2 nm) is highlighted by a dashed rectangle. (d) Graphite is deposited on top of a SiO2/Si substrate with an oxide thickness of ΔSiO2 = 500nm.

[Nano Lett., Vol. 7, No. 9, 2007]

Any of you have produced Graphene ?

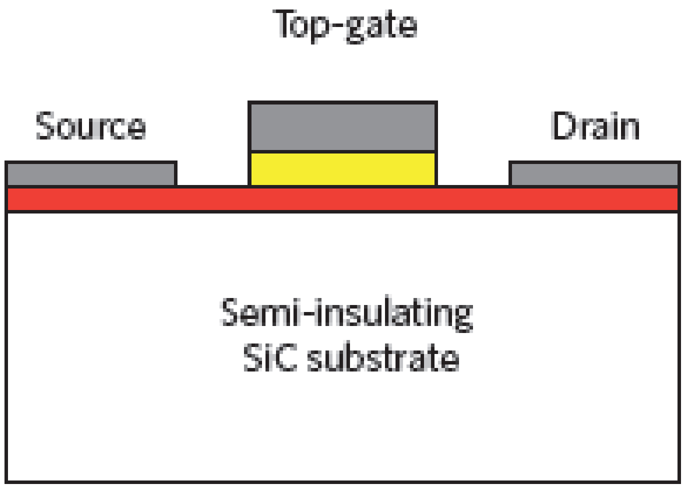
- Graphene has of course always existed as a building block of graphite => One millimeter of graphite consists of three million layers of graphene stacked on top of each other.

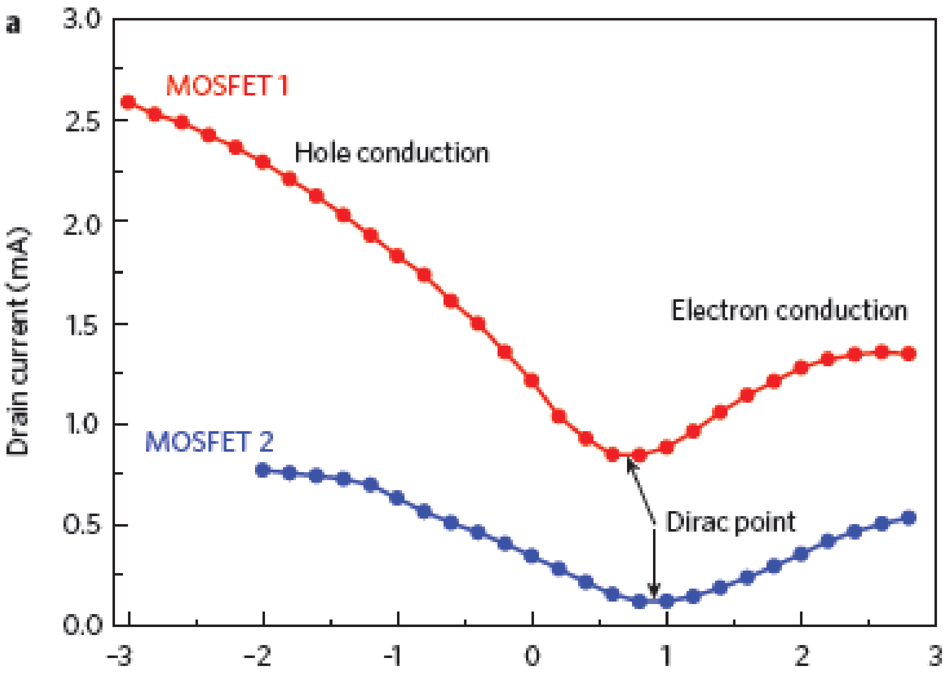




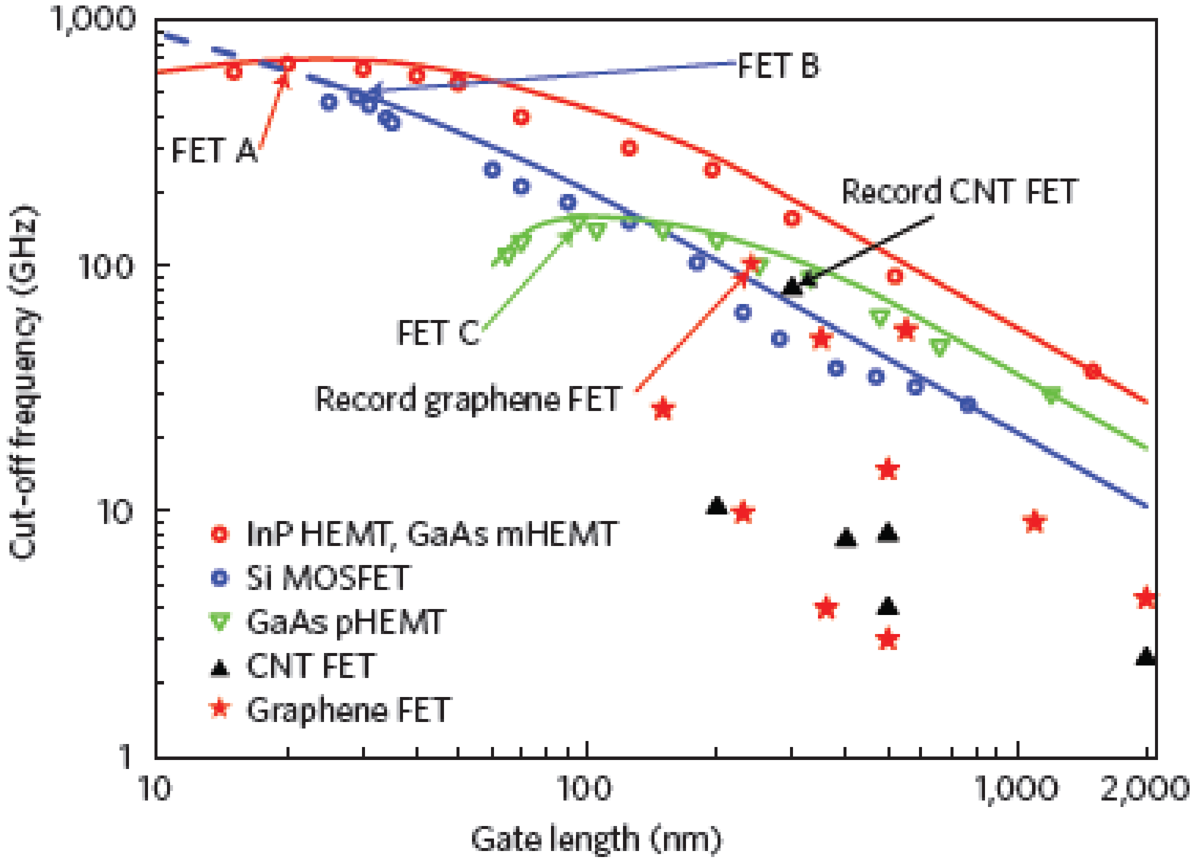
"…everyone who has used an ordinary pencil has probably produced graphene-like structures without knowing it." *[HTTP//KVA.SE]*

Transistor structure





Graphene *vs* Carbon Nano tubes FETs



Let us see what Japanese are saying about Graphene

Material properties at a glance

- A new class of two dimensional materials, based on carbon
- One atom thick - the thinnest material
- Mechanically the strongest - about 200 times the strength of steel
- As a conductor of electricity it performs as well as copper. The sheet conductivity of a 2D material is given by $\sigma = en\mu$. The mobility is theoretically limited to μ=200,000 $cm^2V^{-1}s^{-1}$ by acoustic phonons at a carrier density of $n = 10^{12}$ cm^{-2}. The 2D sheet resistivity, also called the resistance per square, is then 31 Ω.
- As a conductor of heat it outperforms all other known materials. The thermal conductivity of graphene is dominated by phonons and has been measured to be approximately 5000 $Wm^{-1}K^{-1}$. Copper at room temperature has a thermal conductivity of 401 $Wm^{-1}K^{-1}$. Thus graphene conducts heat 10 times better than copper.
- It is almost completely transparent, it absorbs only 2.3% of the light intensity, independent of the wavelength. Suspended graphene does not have any color.
- So dense that not even helium, the smallest gas atom, can pass through it.

[http://static.nobelprize.org/nobel_prizes/physics/laureates/2010/sciback_phy_10.pdf]

Future applications

- Graphene's conductivity can be modified over a large range either by chemical doping or by an electric field.
- The mobility of graphene is very high which makes the material very interesting for electronic high frequency applications.
- Since graphene is a transparent conductor it can be used in applications such as touch screens, light panels and solar cells, where it can replace the rather fragile and expensive Indium-Tin-Oxide (ITO).
- Recently it has become possible to fabricate large sheets of graphene. Using near-industrial methods, sheets with a width of 70 cm have been produced.
- Flexible electronics and gas sensors are other potential applications.
- The quantum Hall effect in graphene could also possibly contribute to an even more accurate resistance standard in metrology.
- New types of composite materials based on graphene with great strength and low weight could also become interesting for use in satellites and aircraft

[http://static.nobelprize.org/nobel_prizes/physics/laureates/2010/sciback_phy_10.pdf]

Impact on the society

- Two dimensional crystal of one carbon atom thick layer "Graphene" shown to exist in a stable state at room temperature

- Graphene exceptional properties originating from the remarkable world of quantum physics proven

- The discovery opens a new research field in physics and material science – more than 7000 scientific papers published since 2004

- Dramatically accelerated the research on epitaxial graphene

- Many applications are foreseen - Graphene can do everything what was expected from carbon nanotubes but it is superior because it is flat continuous medium, it can be processed by conventional electron lithography and also the heating associated with high resistance at electrical contacts is minimized.

- Graphene will be not just another new material but will find a multitude of applications so that everyone might eventually be influenced by this discovery.

Chip Cooling by Graphene

Summary

- World thinnest material
- Amazing Physical properties
- Excellent electronic properties

Can change electronics

by 2016-2020