Graphene

New Old Material
Promises and Realizations

UCSC

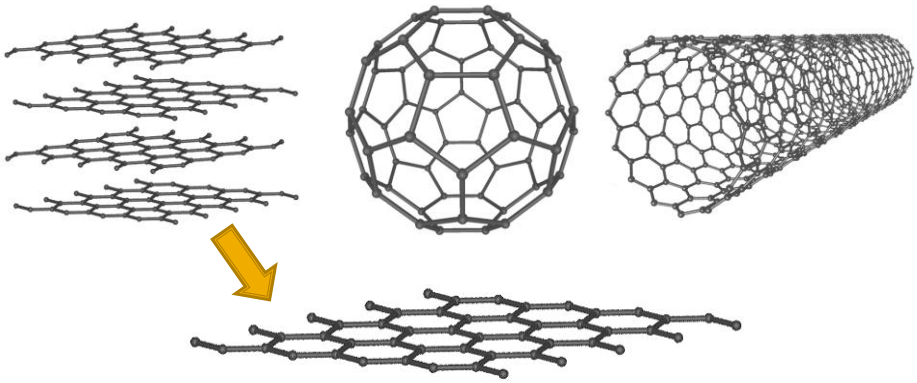
Gey-Hong Gweon

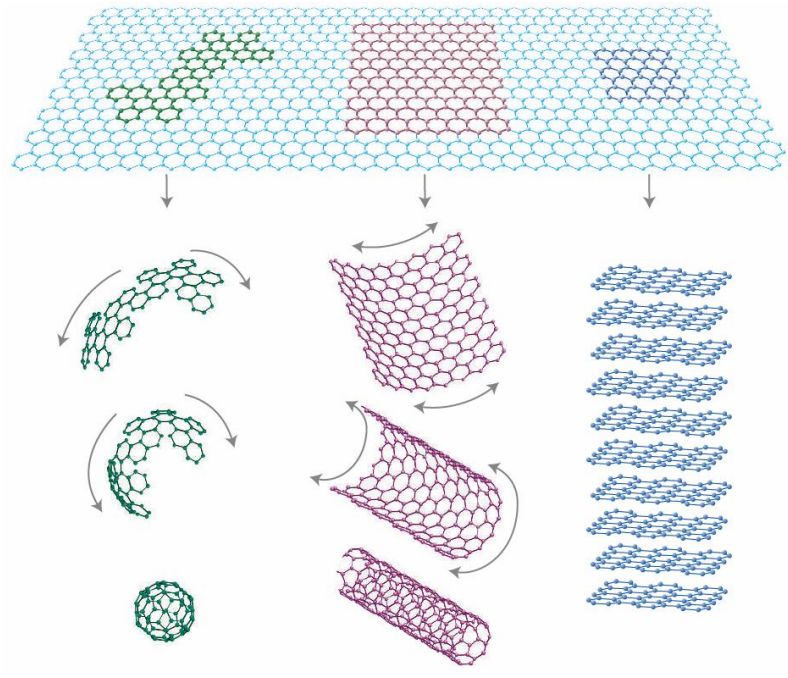
What is graphene?

- "Imagine a piece of paper but a million times thinner. This is how thin graphene is.
- Imagine a material stronger than diamond. This is how strong graphene is [in the plane].
- Imagine a material more conducting than copper. This is how conductive graphene is.
- Imagine a machine that can test the same physics that scientists test in, say, CERN, but small enough to stand on top of your table. Graphene allows this to happen.
- Having such a material in hand, one can easily think of many useful things that can eventually come out. As concerns new physics, no one doubts about it already..."

Andre Geim

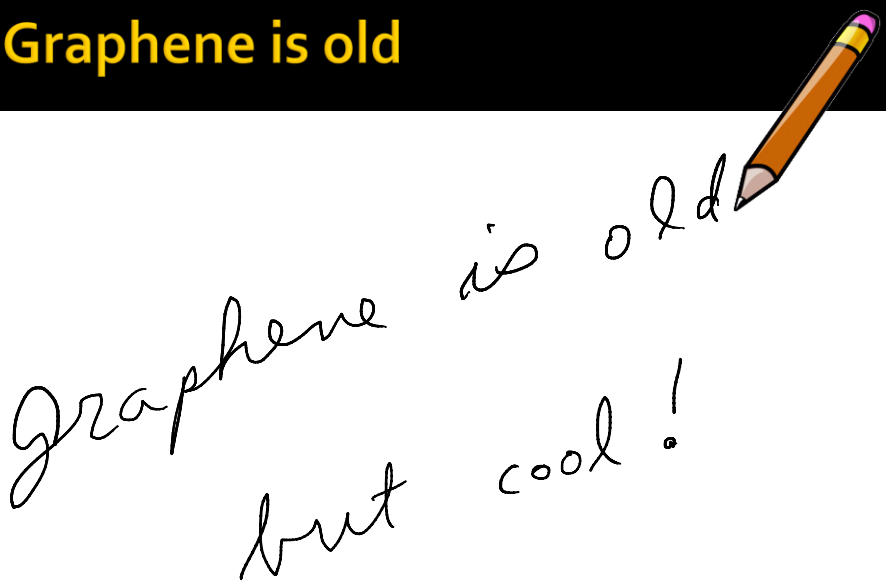
Graphene and carbon allotropes





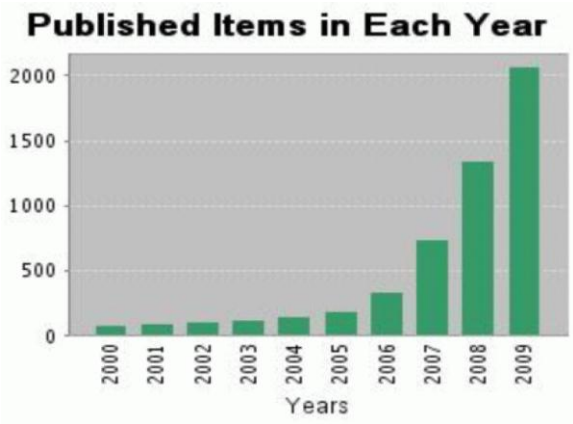
Andre K. Geim and K.S. Novoselov, "The rise of graphene." Nature Materials, 2007

Graphene is old



Graphene is new

3500/2010



Graphene is new

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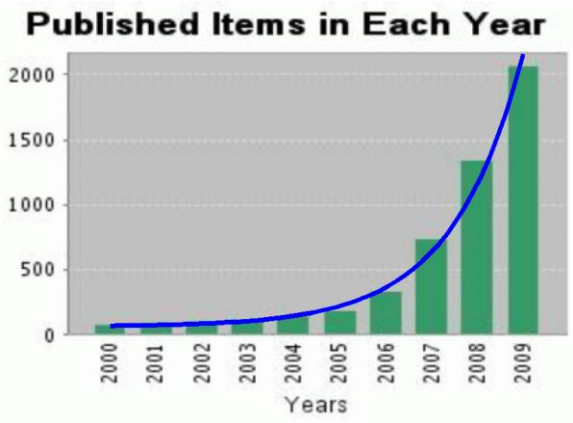


Exponential growth – doubling in about 1.2 years.

Some notable properties

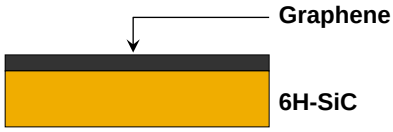
- High mobility – ~ 100,000 $cm^2/(Vs)$ and among the best mobility at room temperature.
- Room temperature Quantum Hall Effect
- High strength – can make it small ("nano") and have it work reliably.
- Thin, nearly transparent electrode.
- Exotic physics (Klein paradox, Non-Fermi liquid, "RVB" interaction, …)

How to make graphene?

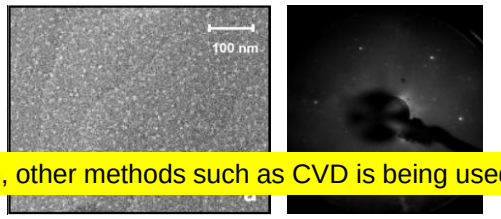
Exfoliation
Pencil "writing"

Novoselev et al. Science v306, 666 ('04)

Thermalization of SiC (~ 1000 C)



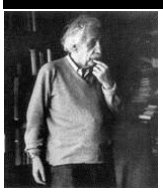
Forbeaux et al. PRB v58, 16396 ('98)

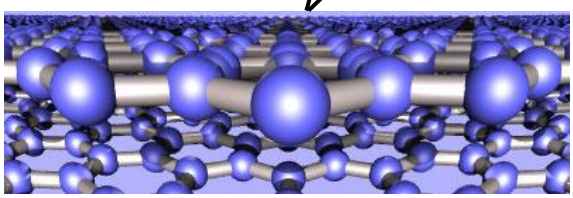


Also, other methods such as CVD is being used.

Number of Layers from XPS Core Level (B. S. Mun)
E. Rollings, GHG, et al.
J. Phys. Chem. Solids, '06; cond-mat/0512226

Photoemission and Graphene





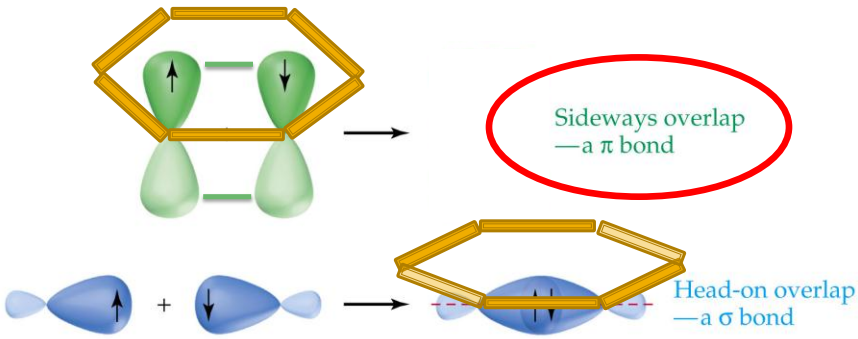
ARPES

XPS

By measuring momentum and energy of the **photoelectron**, we figure out the momentum and energy of the **electron inside the material** of our interest like graphene.

Organic Chemistry: π and σ bonds

- Two side-to-side $2p_z$ orbitals form a π bond.
- Two co-axial $2p$ or sp orbitals form the σ bond.



McMurray and Fay. *Chemistry* 4th ed., Prentice-Hall, 2004.

Ideal Graphene Dispersion

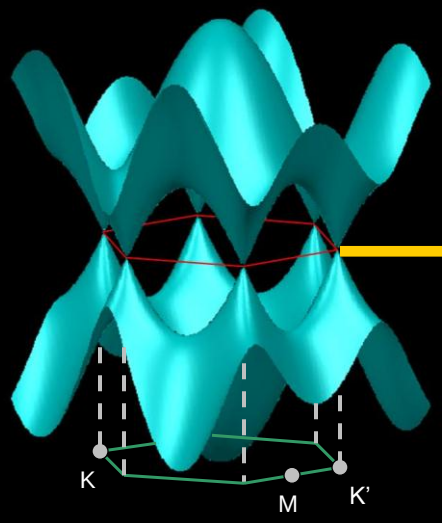
$$\epsilon(\mathbf{q}) = \pm t_0 \sqrt{1 + 4\cos(\sqrt{3}q_y a/2)\cos(q_x a/2) + 4\cos^2(q_x a/2)}.$$

Two inequivalent vertex points of the Brillouin zone:

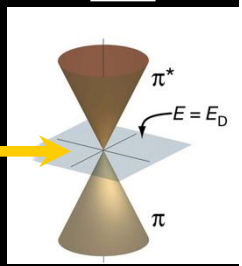
the K and K' points.

(called valleys)

The low energy bulk bands are near these points.

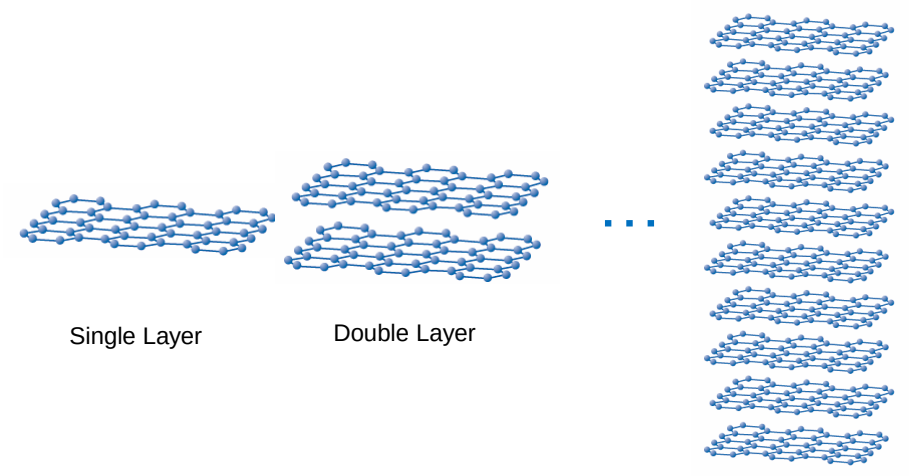


Low energy is like a massless 2D Dirac model

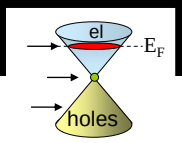


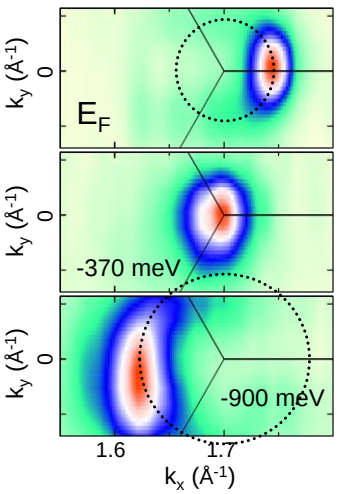
Dispersion: http://www.ece.mcgill.ca/~ts7kop/images/graphene_lcao.jpg Dr. Thomas Szkopek, McGill University

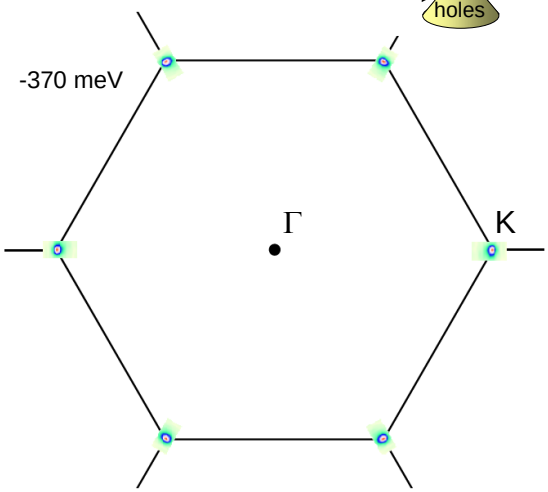
n-layer Graphene



Single Layer Graphene

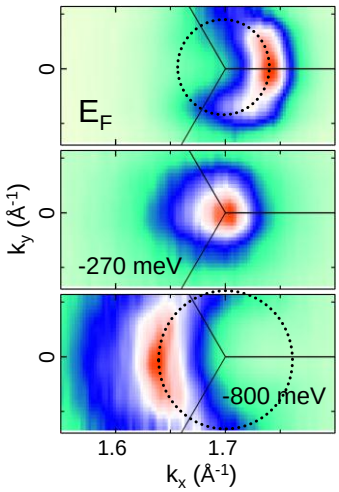


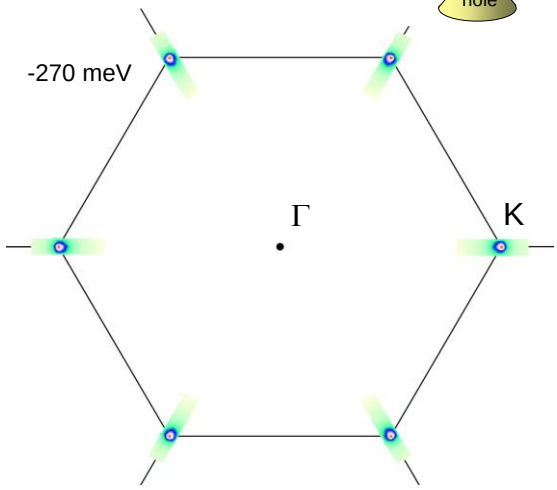


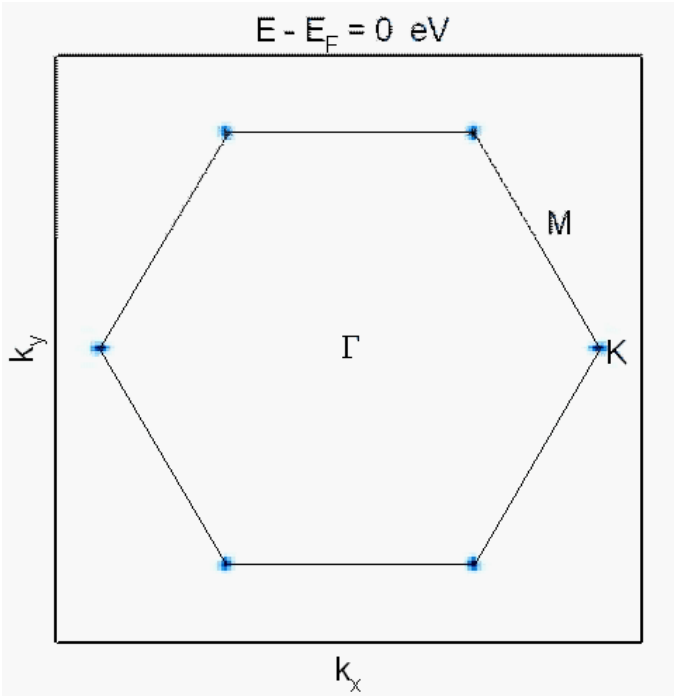


Rollings, GHG et al, J. Phys. Chem. Solids (2006)

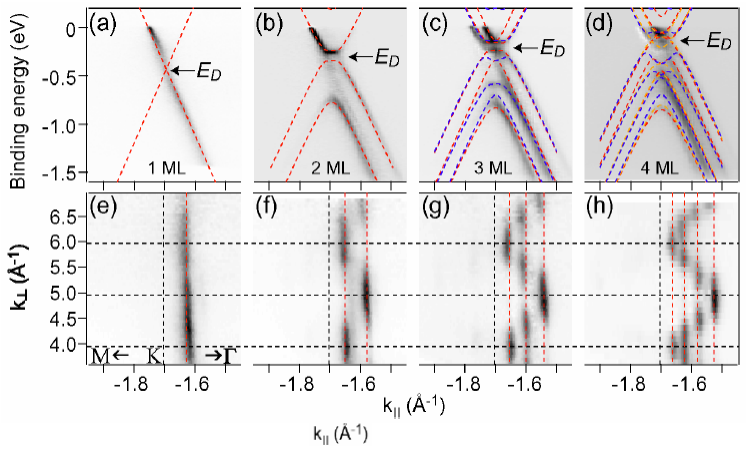
Double Layer Graphene





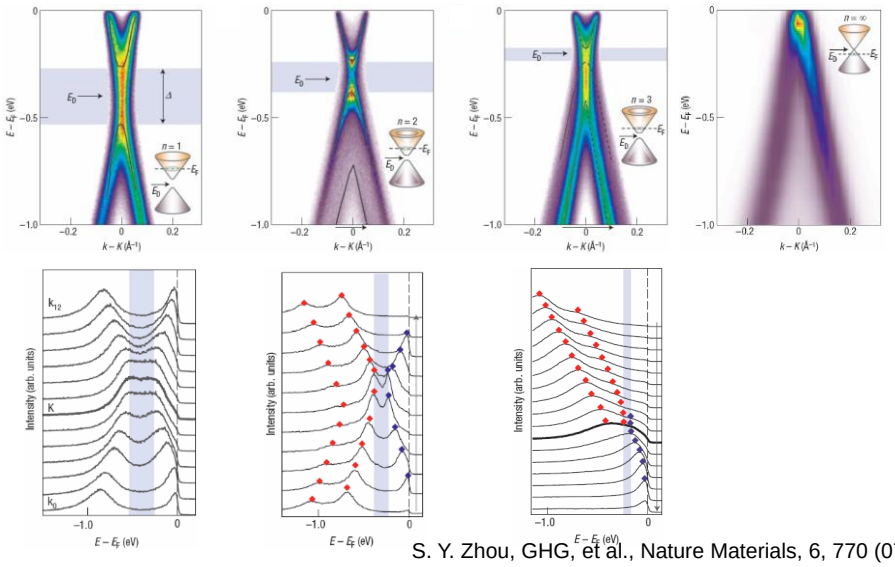


Figuring out the layers in ARPES



Ohta et al., Phys. Rev. Lett. 98, 206802 ('07)

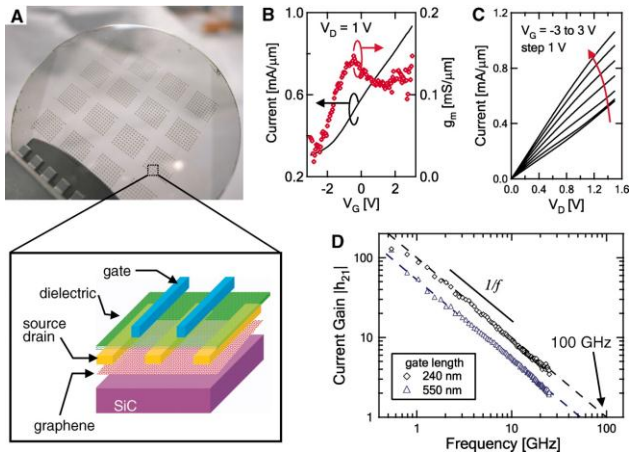
1,2,3, ∞ – Gap in Graphene



S. Y. Zhou, GHG, et al., Nature Materials, 6, 770 (07)

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*

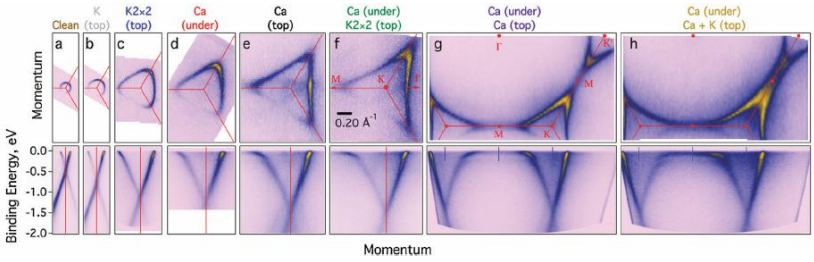


"smallest and fastest!"

IBM T. J. Watson Research Center

Science 2010

Graphene superconductivity?



McChesney et al., Phys. Rev. Lett. 2010

Conclusions

- Graphene is a new material with useful potential applications in technology.
- Graphene is an exciting material for studying novel physics concepts in condensed matter physics and particle physics.