TWO-DIMENSIONAL ATOMIC CRYSTALS

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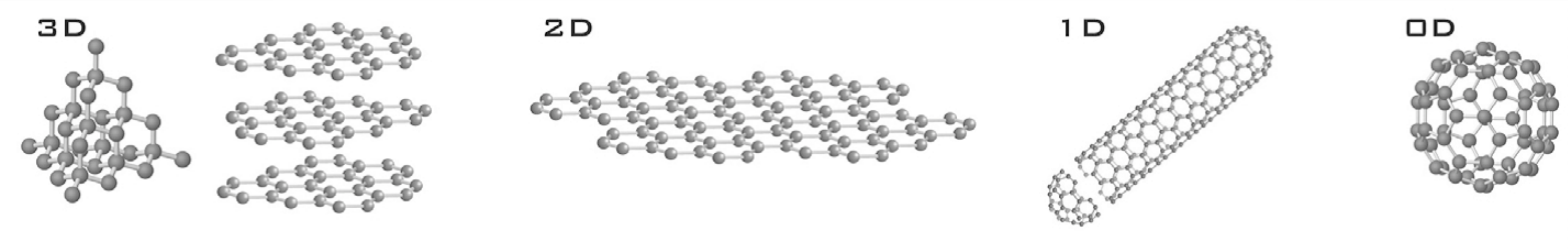
DIMENSIONALITY IS A KEY MATERIAL PARAMETER

- The same chemical compound can exhibit dramatically different properties depending on whether it is arranged in a 0D, 1D, 2D, or 3D crystal structure.
- These different crystal structures are known as **Allotropes.** Different allotropes of the same material have different properties.



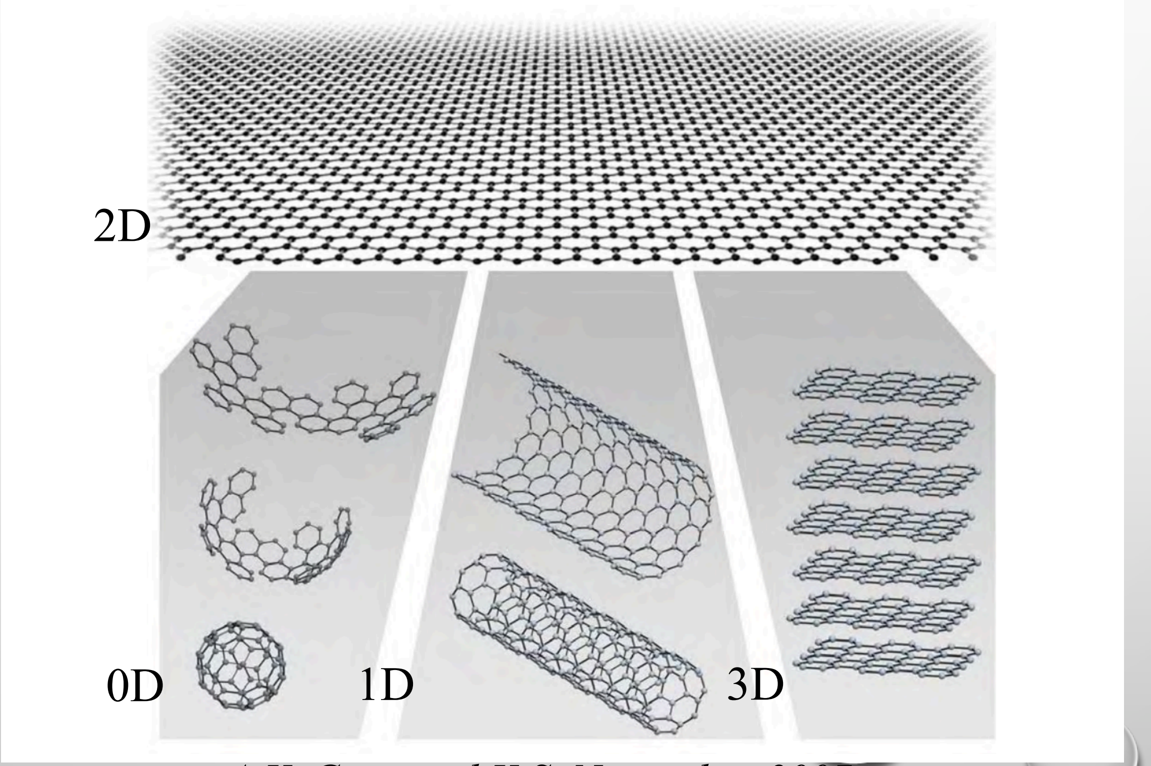
Examples of Allotropes in different dimensions.

In-Yup Jeon, Dong Wook Chang, Nanjundan Ashok Kumar and Jong-Beom Baek, 2011

PURPOSE OF THIS PAPER: WHY STUDY 2D MATERIALS?

- Quasi-0D (e.g., cage molecules), quasi-1D (e.g., nanotubes), 3D crystalline objects are well documented, but **2D is not.**
- Fundamental building element: 2d objects(graphene) are **the building blocks** for other allotropes.

2D structures (top) can be cut and twisted to produce structures in other dimensions (bottom).



A.K. Geim and K.S. Novoselov, 2007

THE GOAL IS TO FABRICATE SINGLE ATOMIC LAYER CRYSTALS

- Why?
  - Stable under ambient conditions

      - exhibit high crystal quality

      - continuous on a macroscopic scale
  - Useful for constructing other configurations

HOW TO CREATE A 2D CRYSTAL

Local order in layered
$NiPS_3$ and $Ni_{0.7}Mg_{0.3}PS_3$,2011

HOW TO CREATE 2D MATERIALS

- **Micromechanical cleavage**

  A fresh surface of a layered crystal was rubbed against another surface. Unexpectedly, only single layered flakes emerged.

- **Optical microscope**

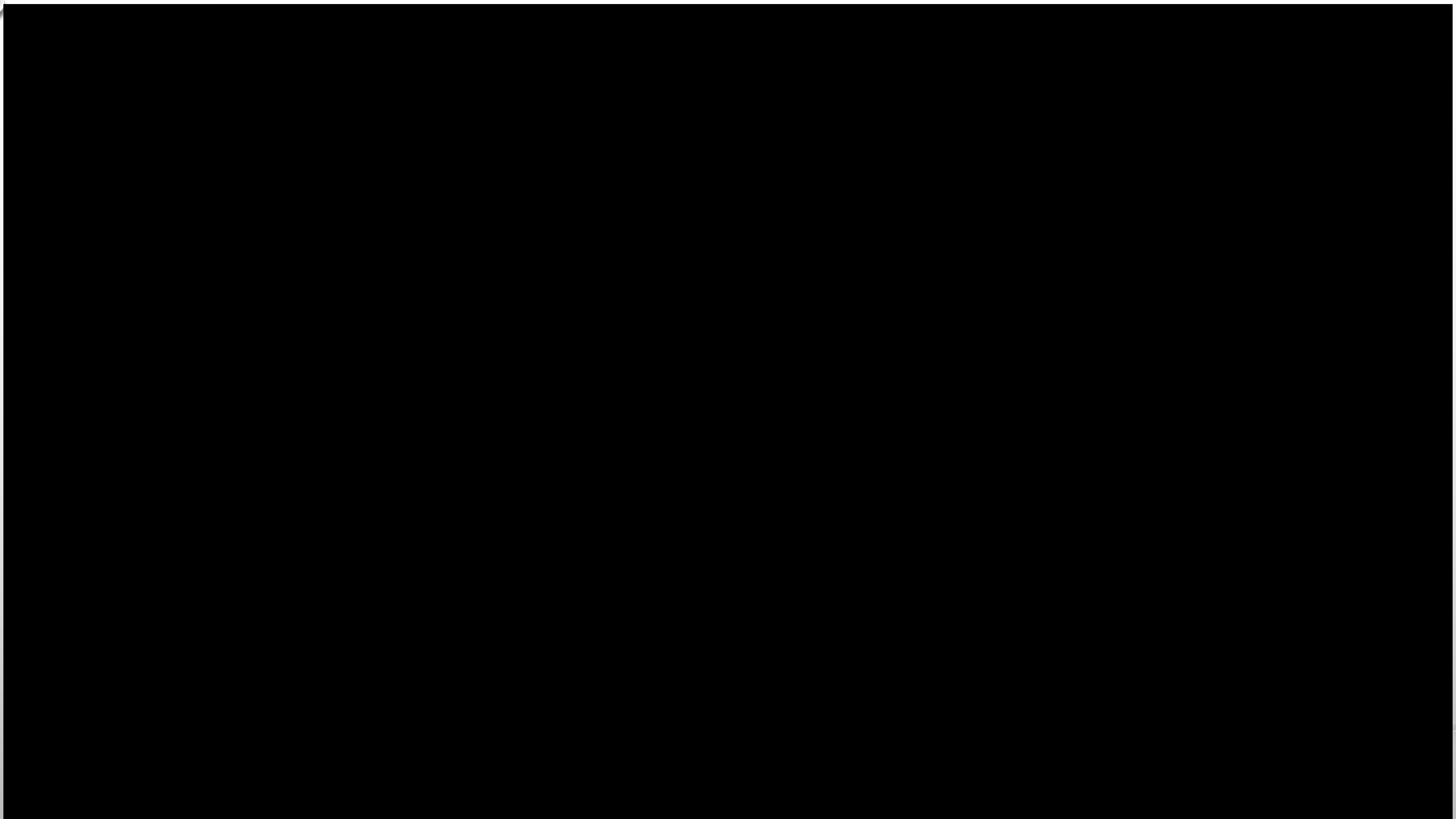
  2D crystallites become visible on top of an oxidized Si (300 nm of thermal SiO_2)

- **Atomic force microscopy (AFM)**

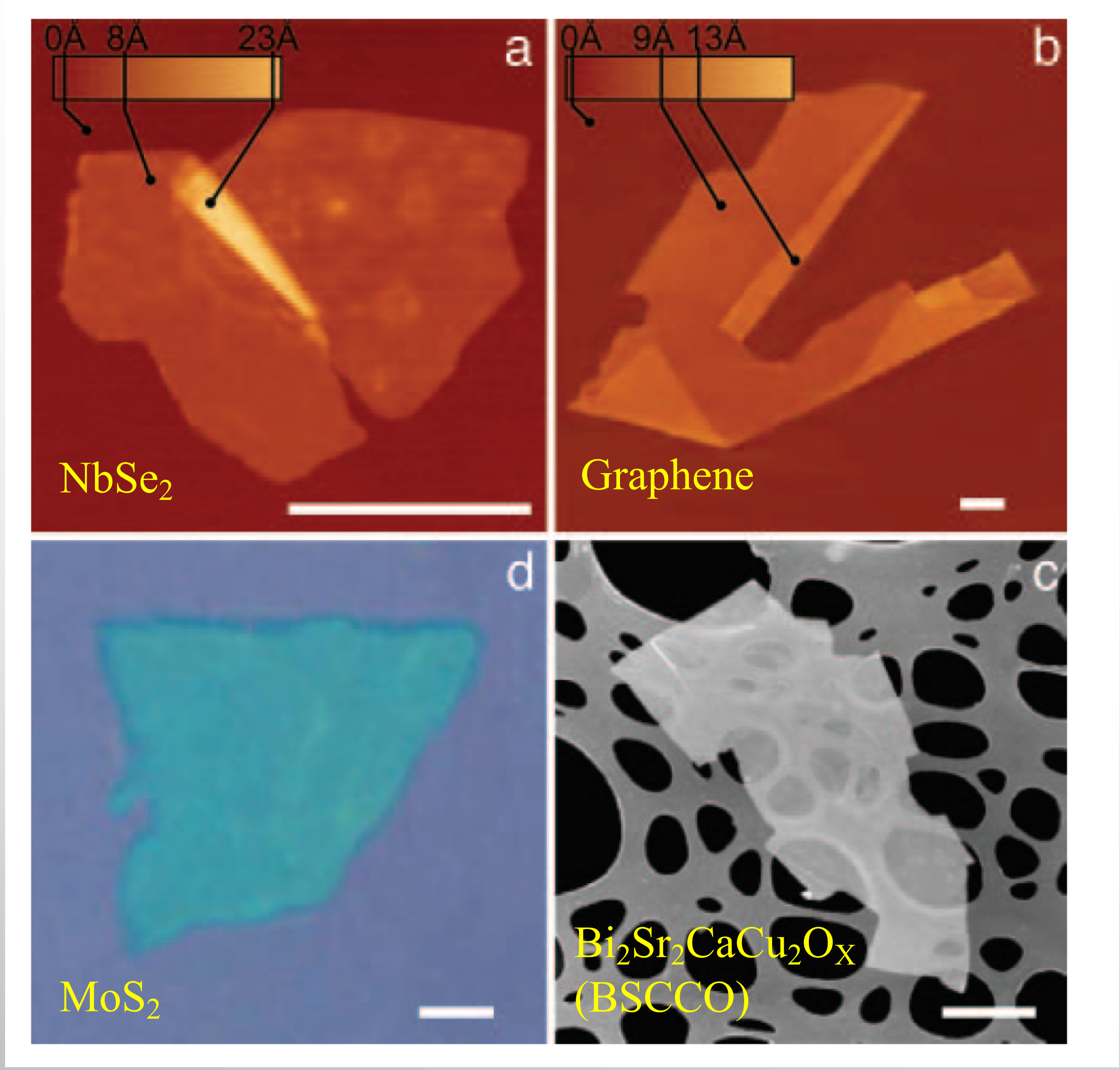
  Single-layer crystals were selected as those exhibiting an apparent thickness of approximately the interlayer distance in the corresponding 3D crystals.

VIDEO DEMONSTRATION

Lacconi et al., National University of Cordoba, Cordoba, Argentina, 2011



IMAGES OF DIFFERENT 2D MATERIALS



- **Process:**
  (a) and (b) --atomic force microscopy
  (c) --scanning electron microscopy
  (d) --optical microscope. (All scale bars: 1um)

- **Base Material:**
  (a), (b) and (d) --on top of an oxidized Si wafer
  (c) --on top of a hole-filled carbon film

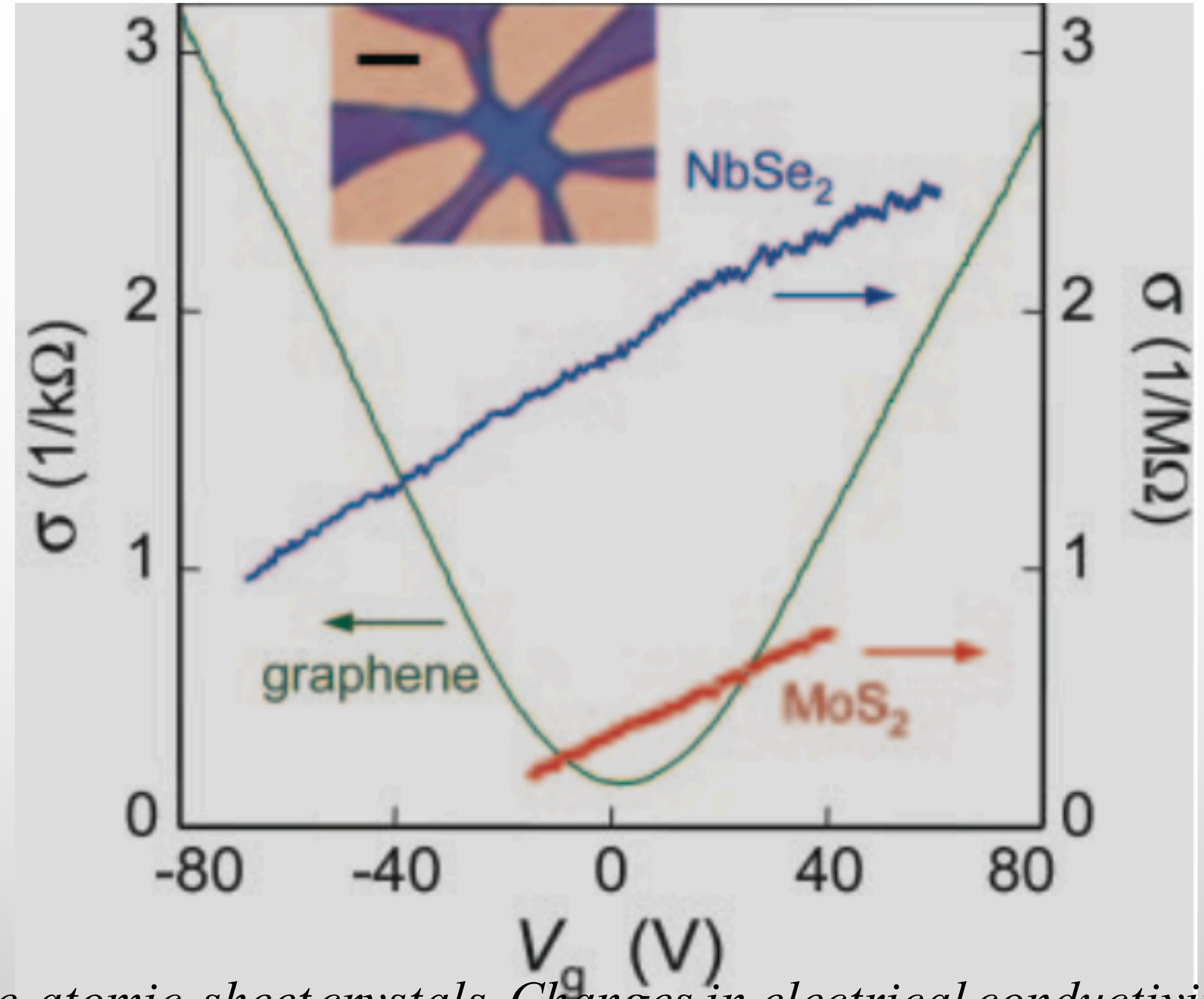
WHY WERE 2D CRYSTALS NOT DISCOVERED EARLIER?

1. Monolayers are in a great **minority** among accompanying thicker flakes.
2. 2D crystals have **no clear signatures** in transmission electron microscopy.
3. Monolayers cannot be seen in an optical microscope **on most substrates** (e.g., on glass or metals).
4. Atomic force microscopy is the only method to identify single-layer crystals, but it has a very **low throughput**.
5. **Unclear** whether it is possible to create free-standing atomic layers

ELECTRICAL CONDUCTIVITY OF THE SELECTED FIVE 2D MATERIALS

Material	Conducting Properties
2D $Bi_2Sr_2CaCu_2O_x$	highly insulating
BN	highly insulating
$NbSe_2$	metallic with a pronounced electric field effect
MoS_2	metallic with a pronounced electric field effect
2D graphite	metallic with a pronounced electric field effect

CONDUCTIVITY IS LINEARLY DEPENDENT ON GATE VOLTAGE IN 2D MATERIALS



Electric field effect in single-atomic-sheet crystals. Changes in electrical conductivity σ of 2D $NbSe_2$, 2D MoS_2, and graphene as a function of gate voltage are shown (300 K).

MAIN CONCLUSIONS OF PAPER

- Graphene is either a <u>shallow-gap semiconductor</u> or a <u>small-overlap semimetal</u>, in which concentration of 2D electrons and holes (induced by gate voltage) up to $n \approx 10^{13}$ cm^{-2}.

- 2D $NbSe_2$ was a <u>semimetal</u> and 2D MoS_2 was a <u>heavily doped semiconductor</u>, both are found to be electron conductors with $n \approx 10^{12}$-$10^{13} cm^{-2}$.

- The electron concentration in 2D $NbSe_2$ is <u>two orders of magnitude</u> smaller than carrier concentrations per monolayer in 3D $NbSe_2$. This indicates significant changes in the energy spectrum of $NbSe_2$ from a normal metal in 3D to a semimetal in 2D.

CITATION ANALYSIS

1. Published in July, 2005.

2. Citation number: 5160 times, according to Google Scholar
3750 times, according to Scopus

3. Citation history according to Scopus:

2016	(3)
2015	(672)
2014	(707)
2013	(623)
2012	(512)
2011	(381)
2010	(329)
2009	(220)
2008	(163)
2007	(103)
2006	(35)
2005	(2)

RESEARCH HAS EVOLVED SINCE THE PAPER WAS PUBLISHED

- Graphene： A typical 2D crystal has become the hot research area.

  Geim, Andre K., and Konstantin S. Novoselov. "The rise of graphene." *Nature materials* 6.3 (2007): 183-191.

- Synthesis： Large-area synthesis methods have been developed.

  Wu, Wei, et al. "Growth of single crystal graphene arrays by locally controlling nucleation on polycrystalline Cu using chemical vapor deposition." *Advanced Materials* 23.42 (2011): 4898-4903.

- Physical properties： electronic and photovoltaic properties have been studied, making it possible for the industrial applications.

  Neto, AH Castro, et al. "The electronic properties of graphene." *Reviews of modern physics* 81.1 (2009): 109.

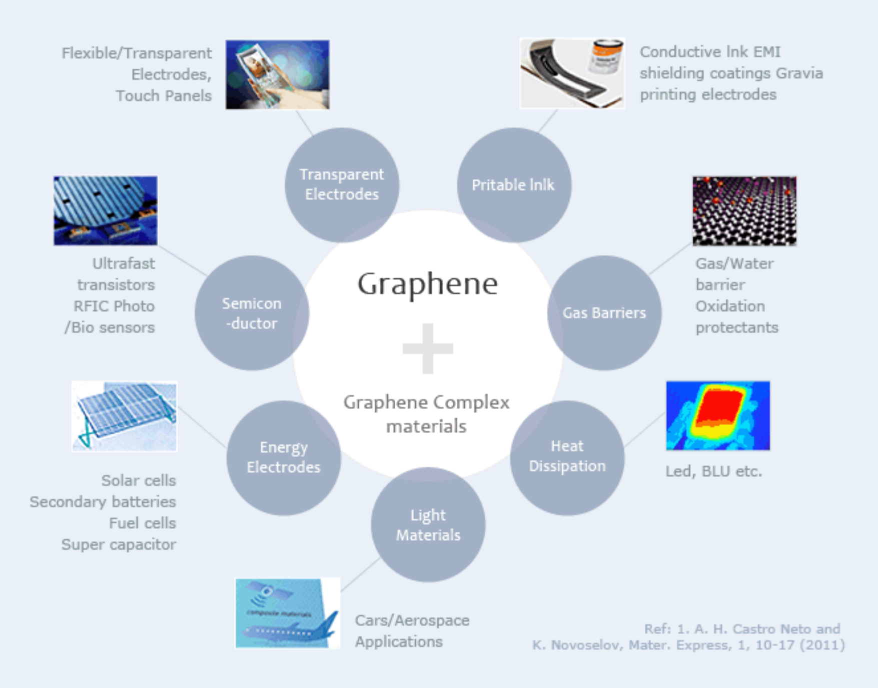
FUTURE APPLICATIONS FOR 2D MATERIALS

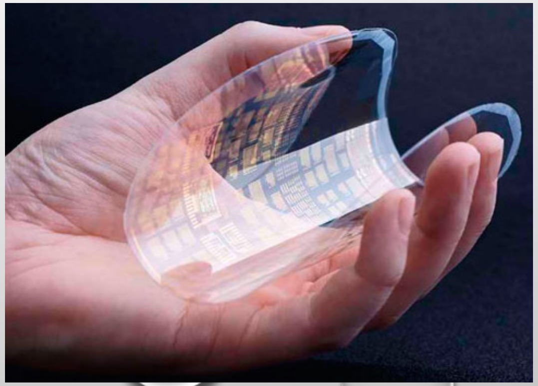
- Electronics

  New transistor, integrated circuit, quantum computer

- Optoelectronics

  Touchscreen, Liquid-crystal display, organic photovoltaic materials





The Nobel Prize in Physics 2010

Photo: U. Montan

Andre Geim

Prize share: 1/2

Photo: U. Montan

Konstantin Novoselov

Prize share: 1/2

The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov *"for groundbreaking experiments regarding the two-dimensional material graphene"*

Thank You!

Questions?