# Interplay between engineering and fundamental research in nanoscience and nanotechnology.

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# How to recognize scientific disciplines (I)?

If it squirms, it's biology.
If it stinks, it's chemistry.
If you can't understand it, it's mathematics.

and…

If it doesn't work, it's physics.

(attr. to Magnus Pyke)

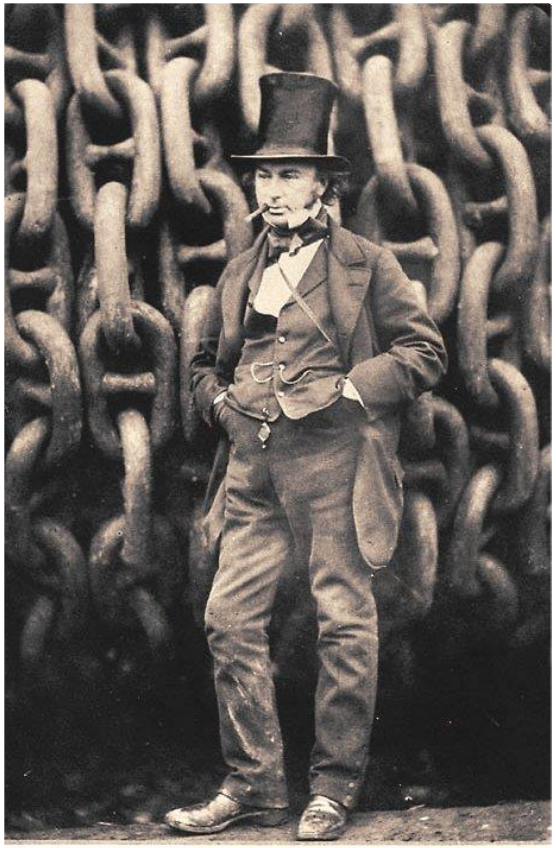
# How to recognize scientific disciplines (II)?

If it works, but you don't understand how,

it's technology !

(unknown author)

# Isambard Kingdom Brunel (1806-1859)
(Nr 2 on list of 100 Greatest Britons)

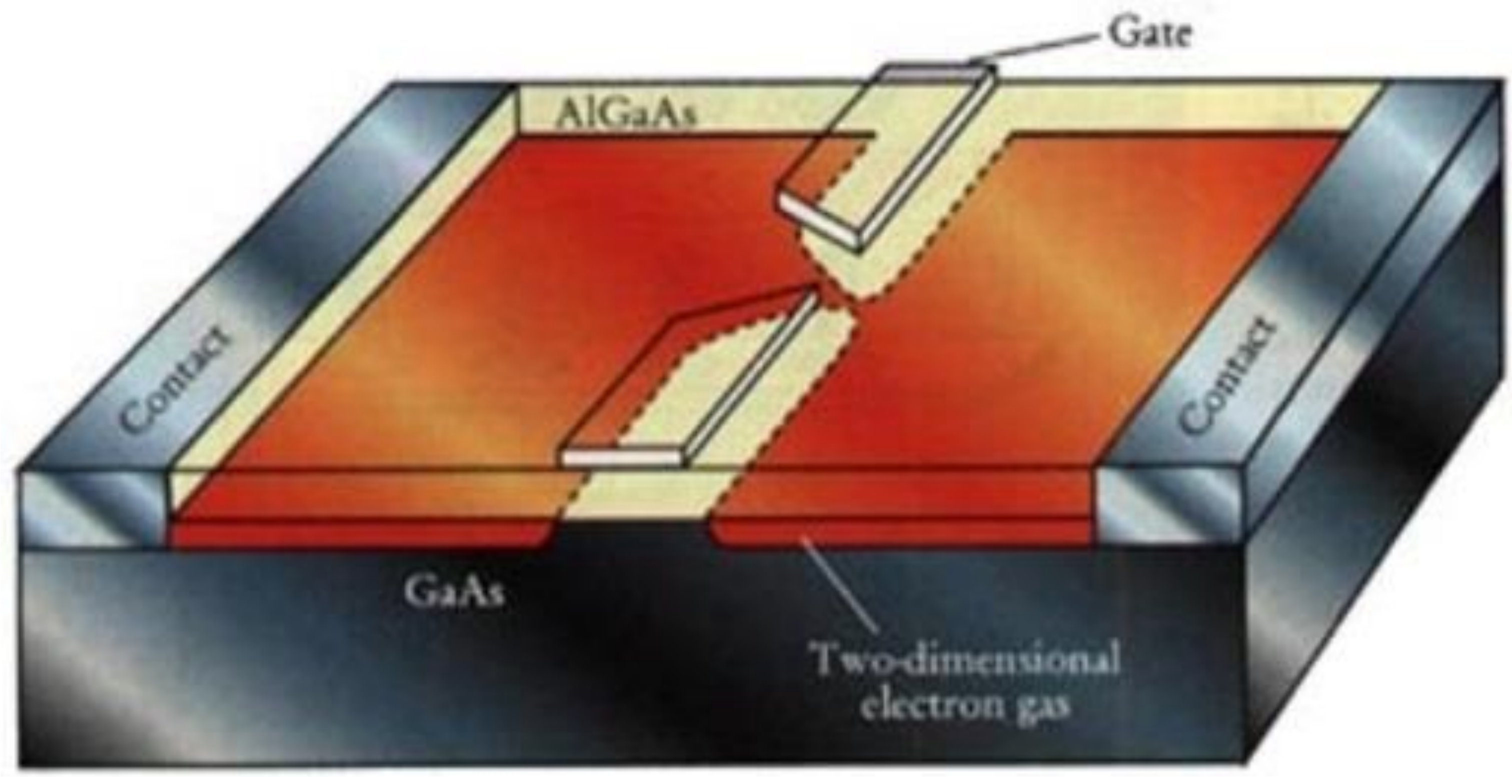


S.S. Great Eastern

Royal Albert Bridge

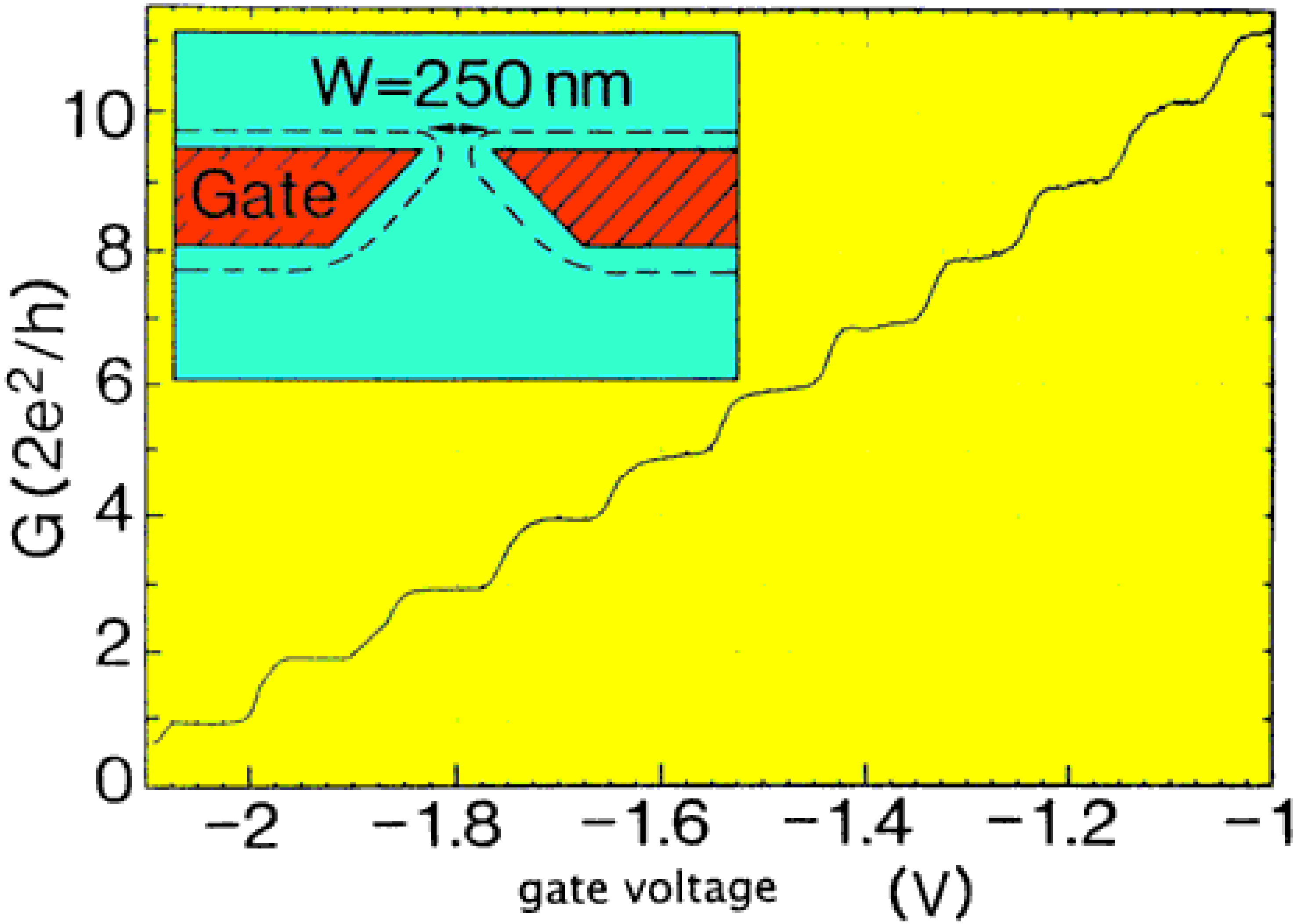
# Brunel's "Atmospheric Railway"

# Quantum point contact ( BJvW1988)

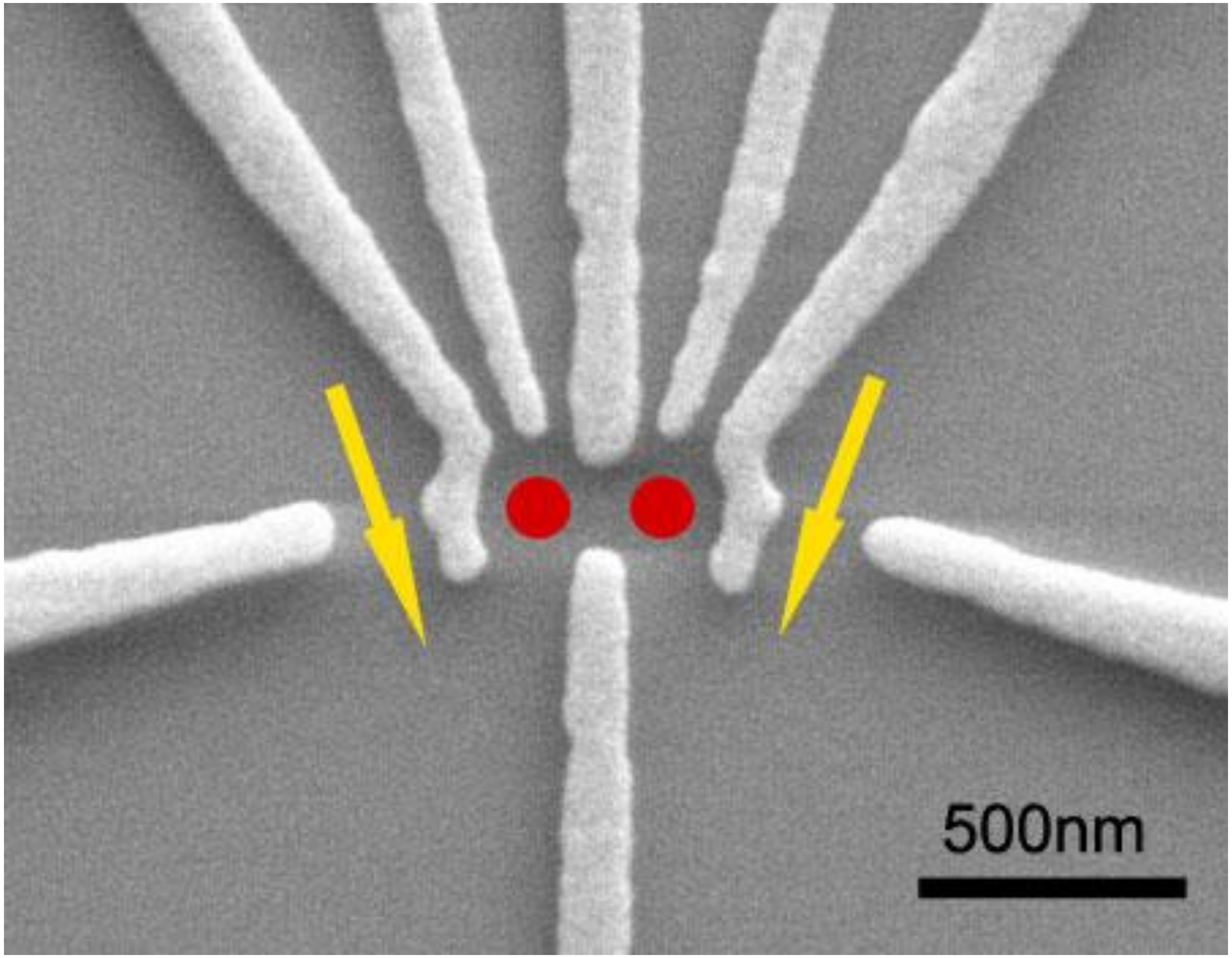



Split-gate technique

# Quantized conductance of one-dimensional electron channels



# Quantum dots and quantum point contacts



# 2010 Nobel Prize for Physics

**Prize motivation:** "for groundbreaking experiments regarding the two-dimensional material graphene"

**Andrei Geim**

**Konstantin Novoselov**

# History of graphene

Early development of graphene electronics

Walt A. de Heer

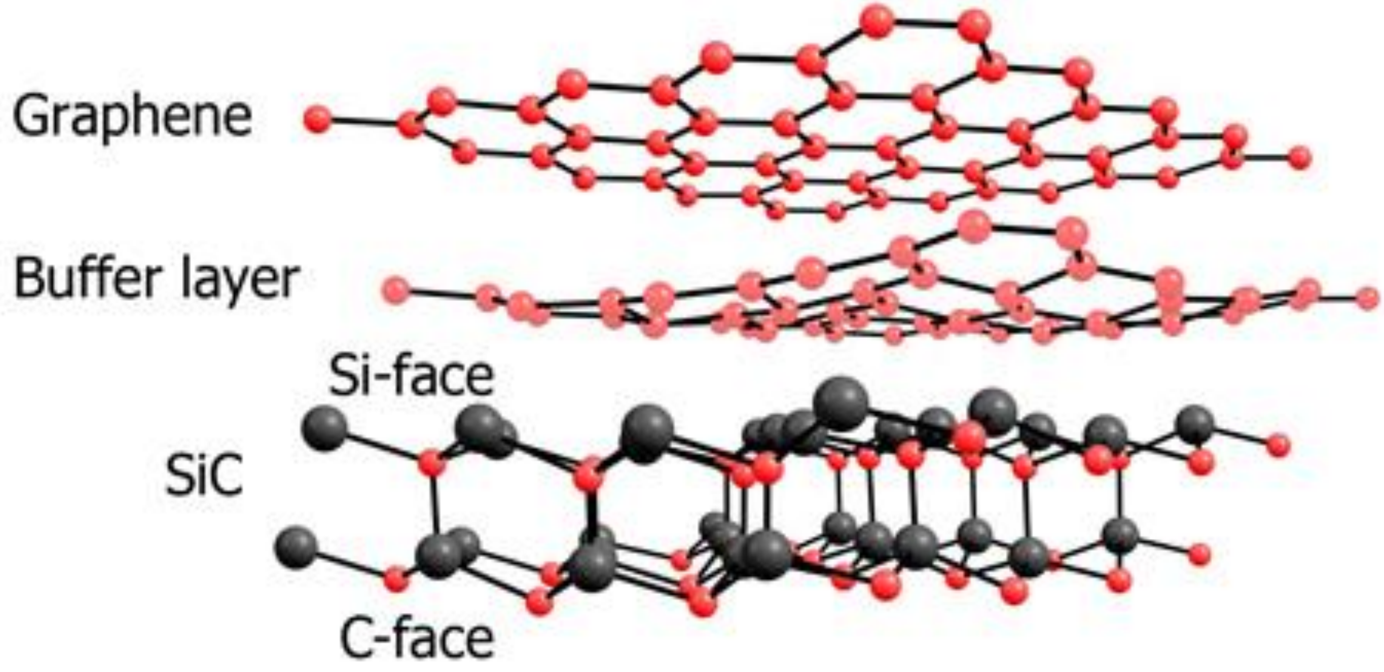
Georgia Institute of Technology

Abstract

Graphene has recently emerged as a material likely to complement or eventually succeed silicon in electronics. From 2001 to 2004, groundbreaking research was pursued behind the scenes at Georgia Tech; various directions were explored, including exfoliation techniques and CVD growth, but epitaxial graphene on silicon carbide emerged as the most viable route. This document provides archival information that may otherwise be difficult to obtain, including two proposals on file with the NSF, submitted in 2001 and 2003, and the first graphene patent, filed in 2003. The 2001 document proposes much of the graphene research carried out during this decade, and the 2003 proposal includes the data that was eventually published in J. Phys. Chem. B in Dec. 2004.

Note: Some personal information has been removed

# Graphene grown on SiC



# "Dutch connection": High Field Magnet Laboratory Nijmegen

Type: Bitter

Max Field: 33.0 tesla

Bore: Ø 32mm at room temp.

Power: 17 MW

Homogeneity: 1x10-3 in 1 cm DSV

# Ig Nobel Prize

Given for research achievements:

"that first make people laugh, and then make them think."

"that cannot or ***should not*** be ***reproduced***."

**2000 Physics** - Presented to Andre Geim of the University of Nijmegen, the Netherlands, and Michael Berry of Bristol University, England, for using magnets to levitate a frog.

Geim later shared the 2010 Nobel Prize in physics for his research on graphene, the first time anyone has been awarded both the Ig Nobel and (real) Nobel Prizes.

# Friday afternoon experiment: Levitating frog

A live frog levitates inside a 32 mm diameter vertical bore of a Bitter solenoid in a magnetic field of about 16 teslas at the High Field Magnet Laboratory of the Radboud University in Nijmegen the Netherlands

But beware of

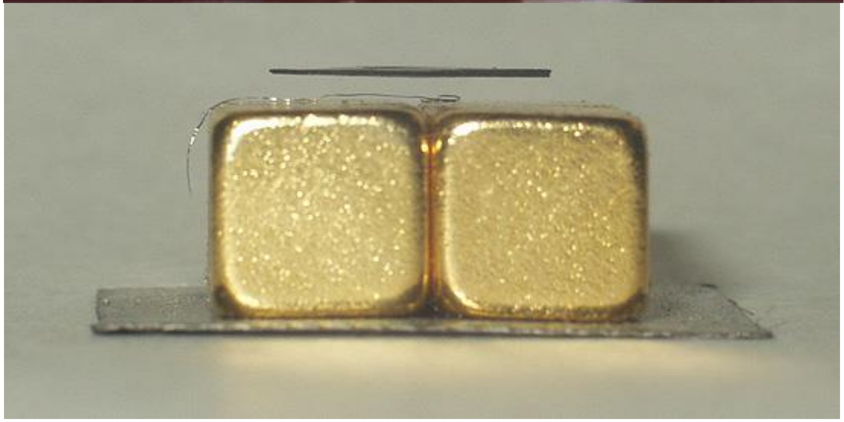
Earnshaw's theorem!

# Earnshaw’s theorem

**Earnshaw's theorem** states that a collection of point charges cannot be maintained in a stable stationary equilibrium configuration solely by the electrostatic interaction of the charges. This was first proven by British mathematician Samuel Earnshaw in 1842. It is usually referenced to magnetic fields, but originally applied to electrostatic fields. It applies to the classical inverse-square law forces (electric and gravitational) and also to the magnetic forces of permanent magnets and paramagnetic materials or any combination, (but not diamagnetic materials).

# Levitating other things…

# Levitating carbon (graphite)



Graphite:

• Pencil lead

• Moderator in nuclear reactors

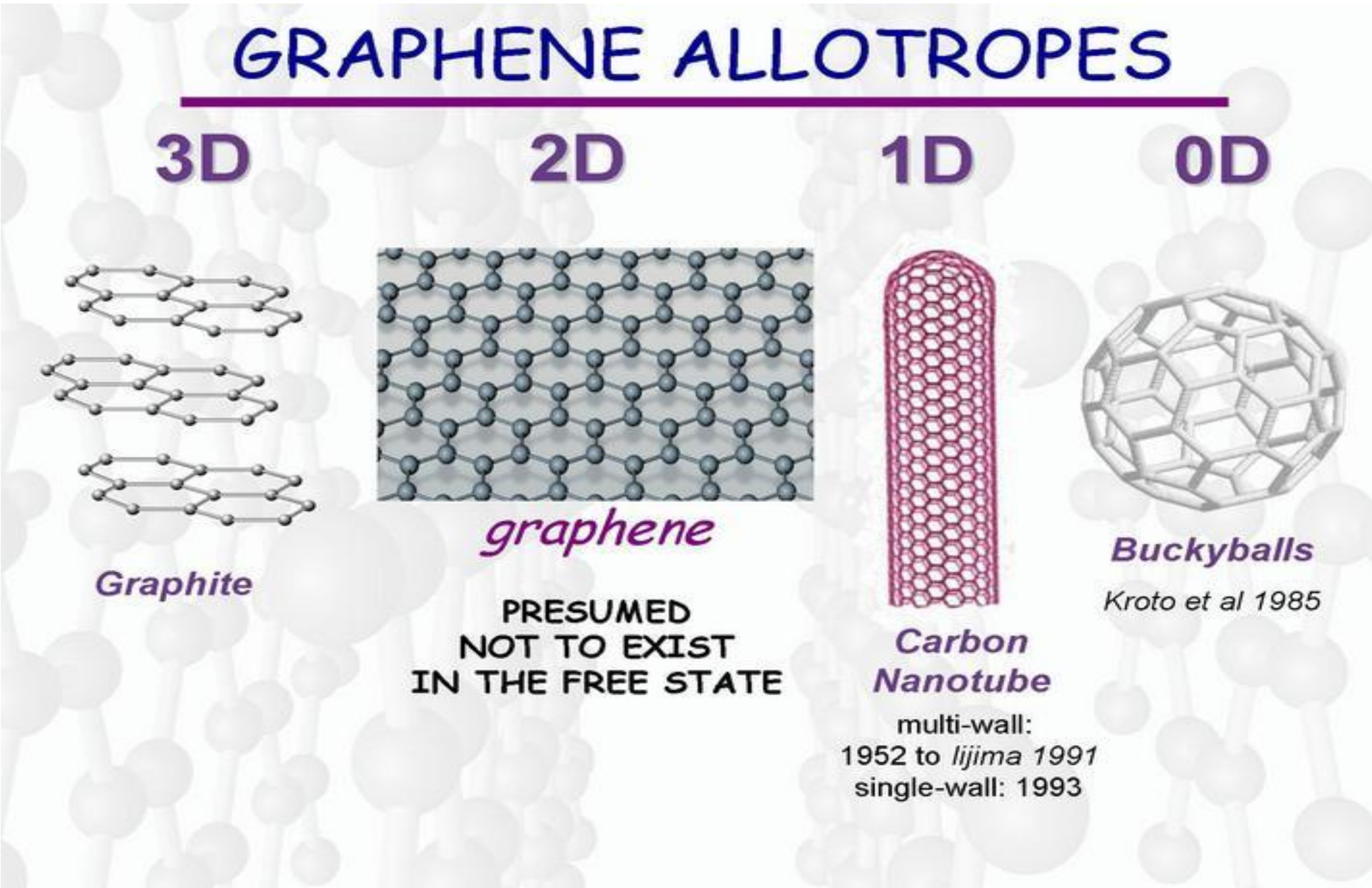
* Layered structure

* Steelmaking industry

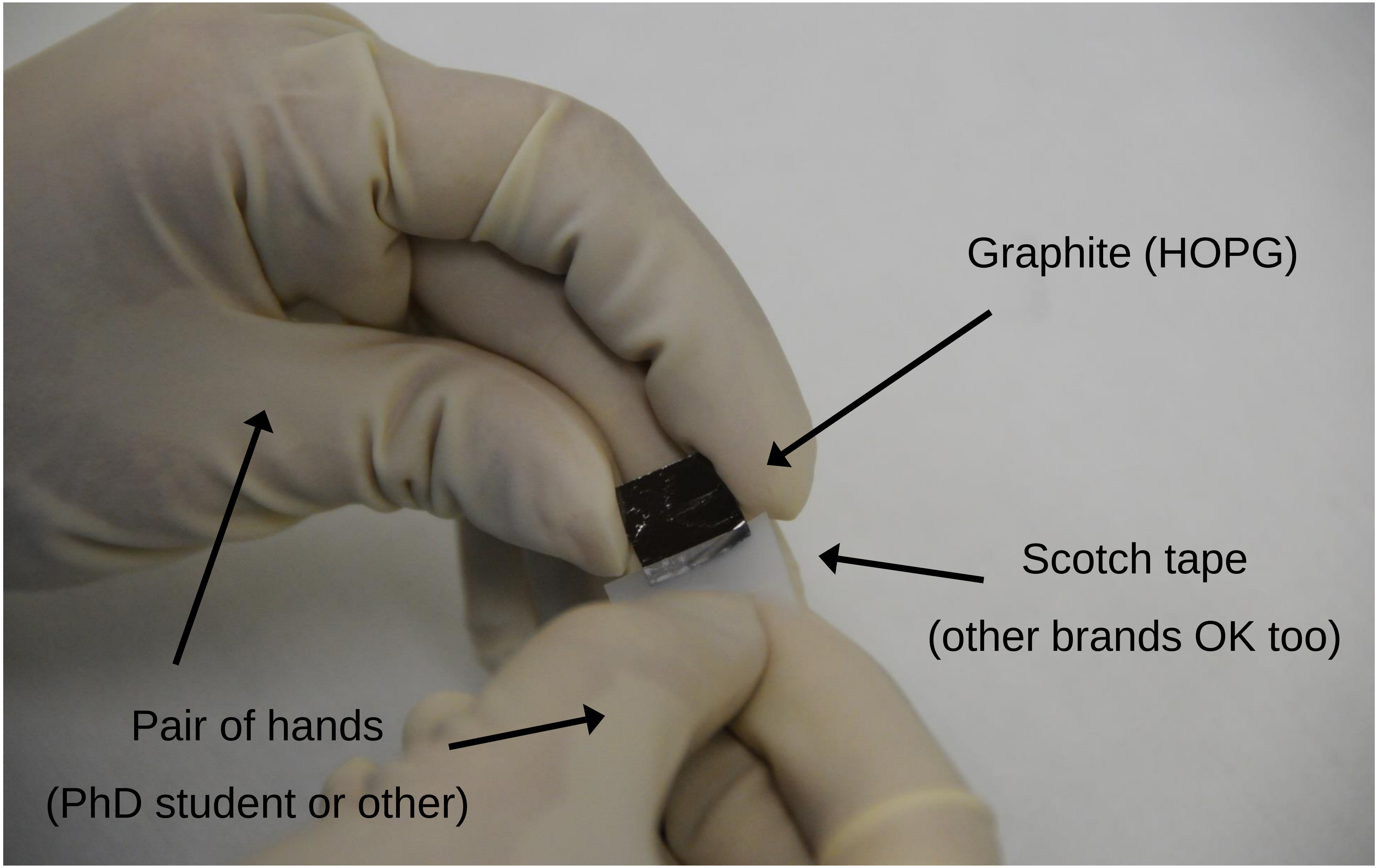
* Lubricant

* Good electrical conductor

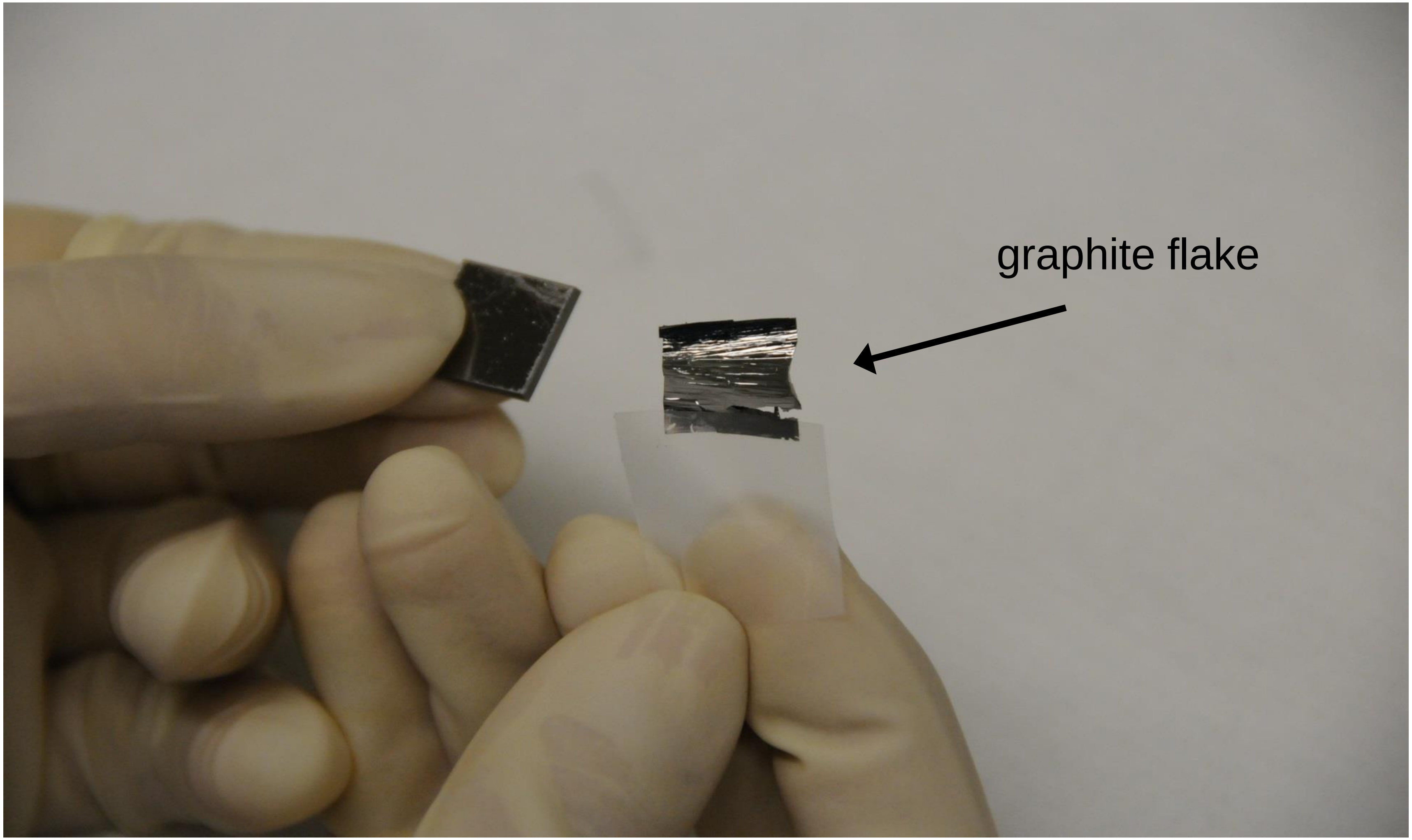
# Carbon comes in different dimensions



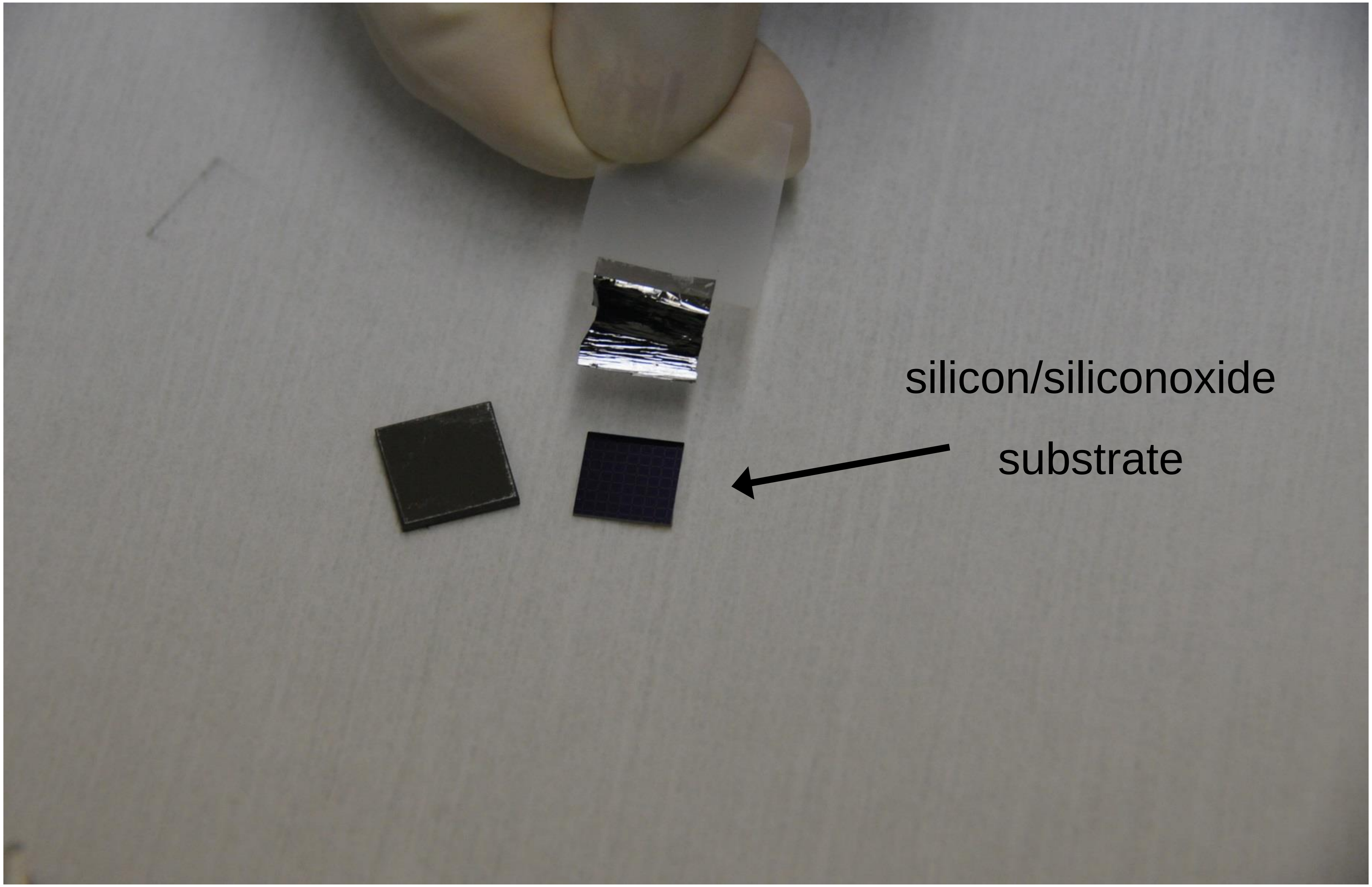
# Scotch tape method (1)



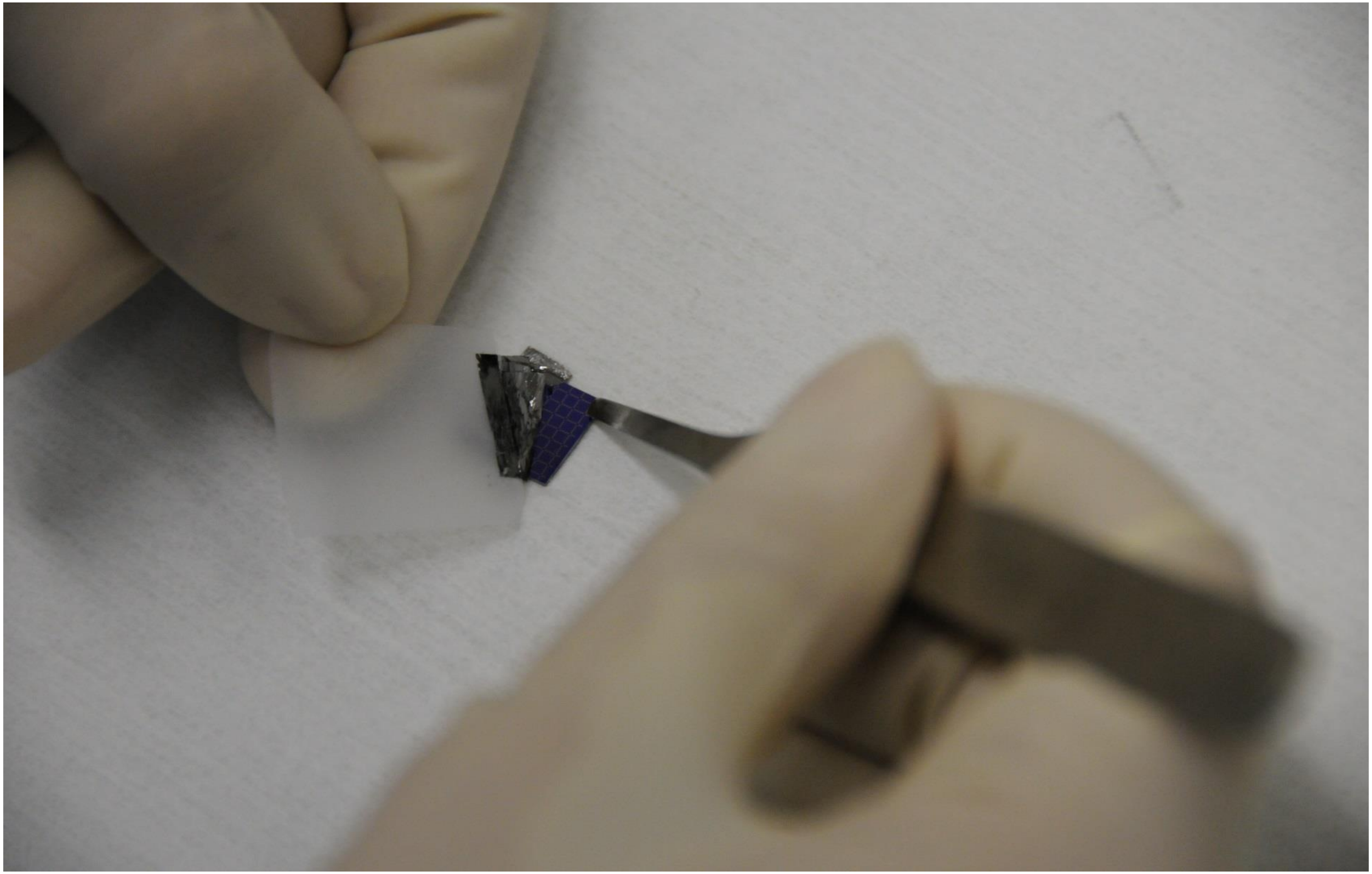
# Scotch tape method (2)



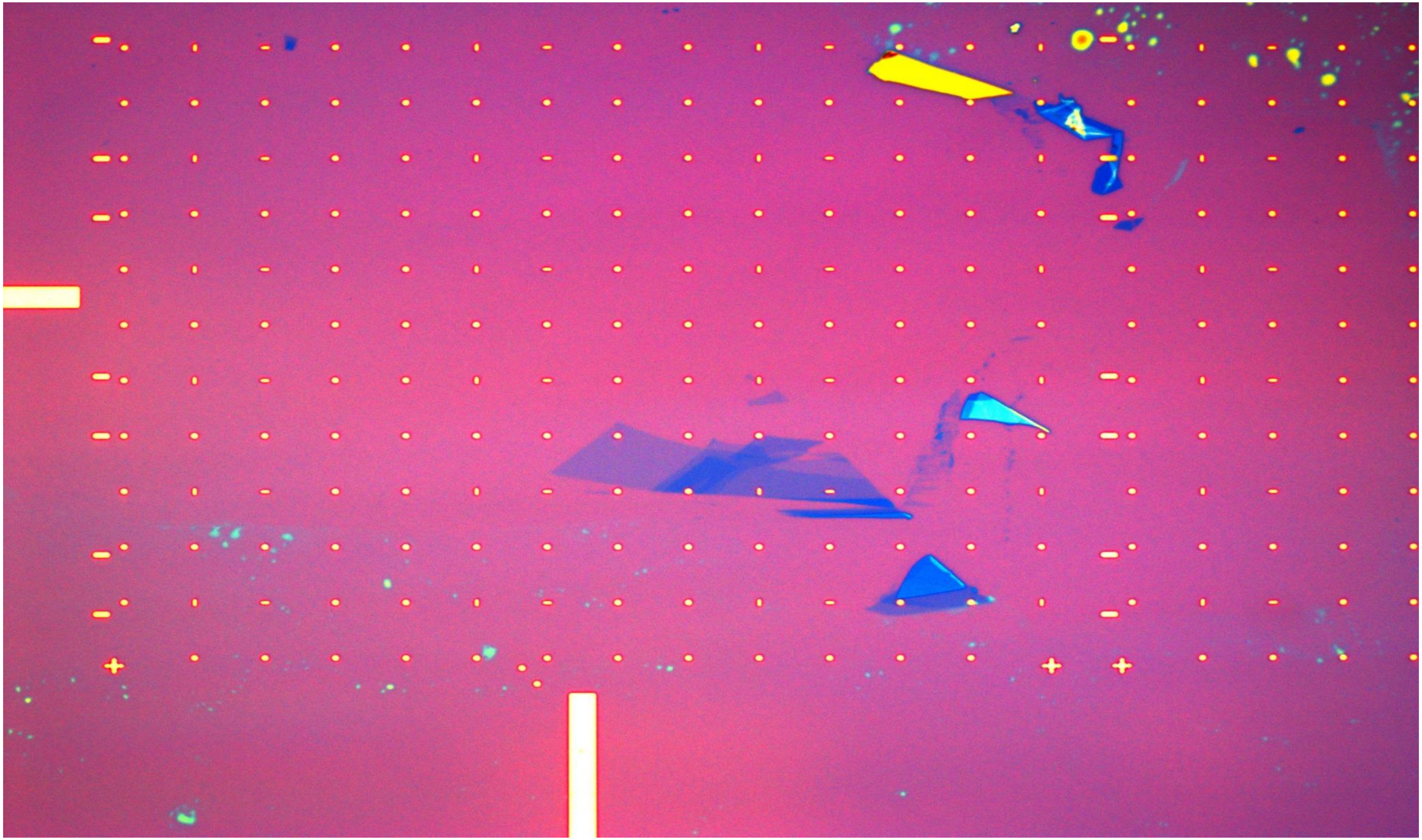
# Scotch tape method (3)



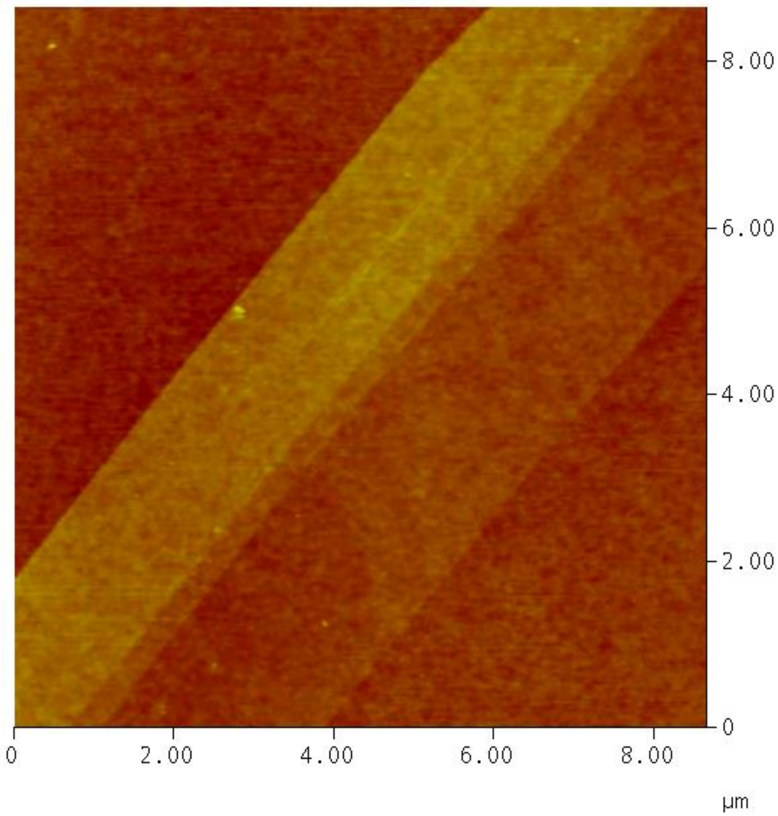
# Scotch tape method (4)

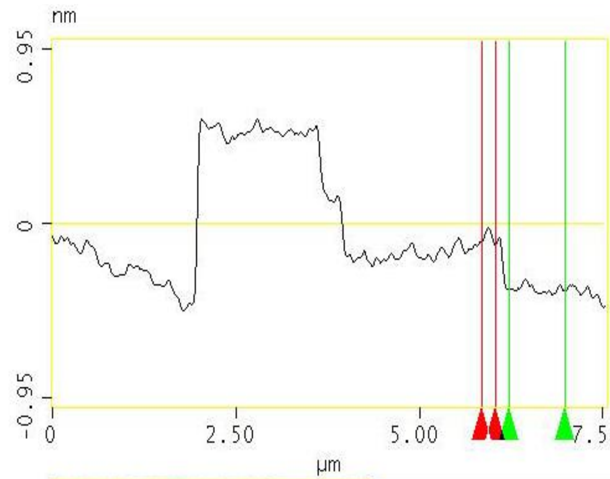


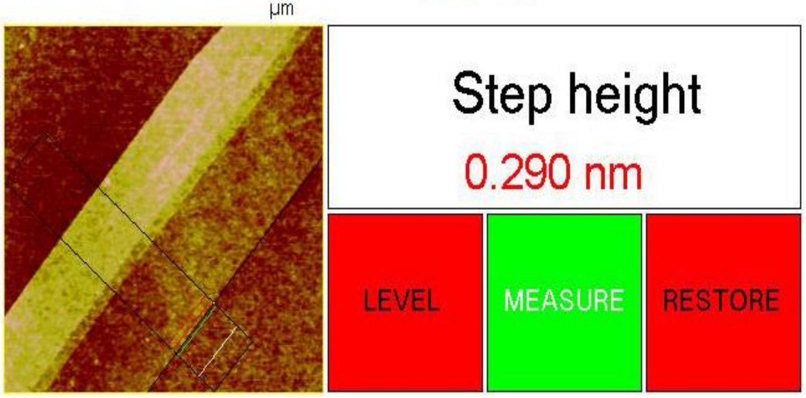
# Graphene (single and multilayer) under the (optical) microscope



# Single graphene layers: Atomic force microscope



# Graphene field effect transistor

Graphene layer

Source

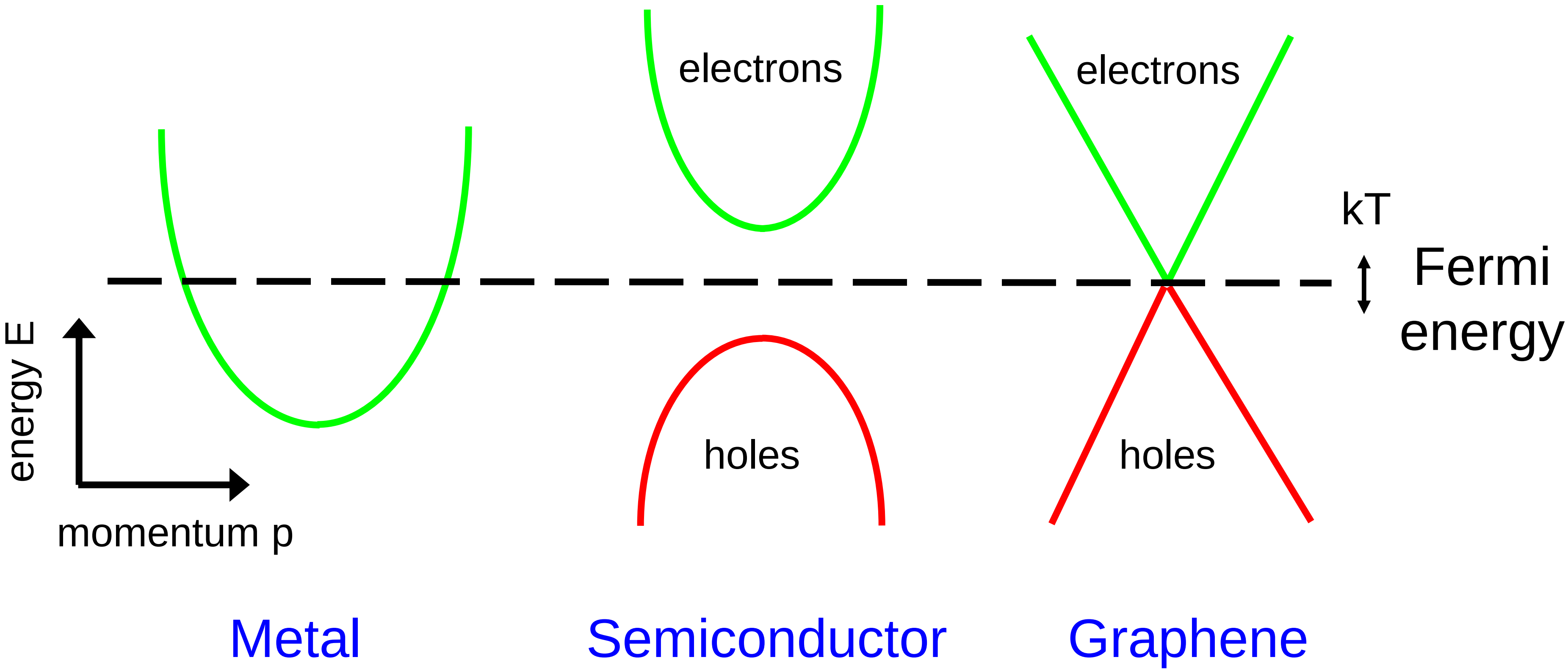
Drain

Doped Si gate induced charge:

$Q=C_g V_g$

No surface states!

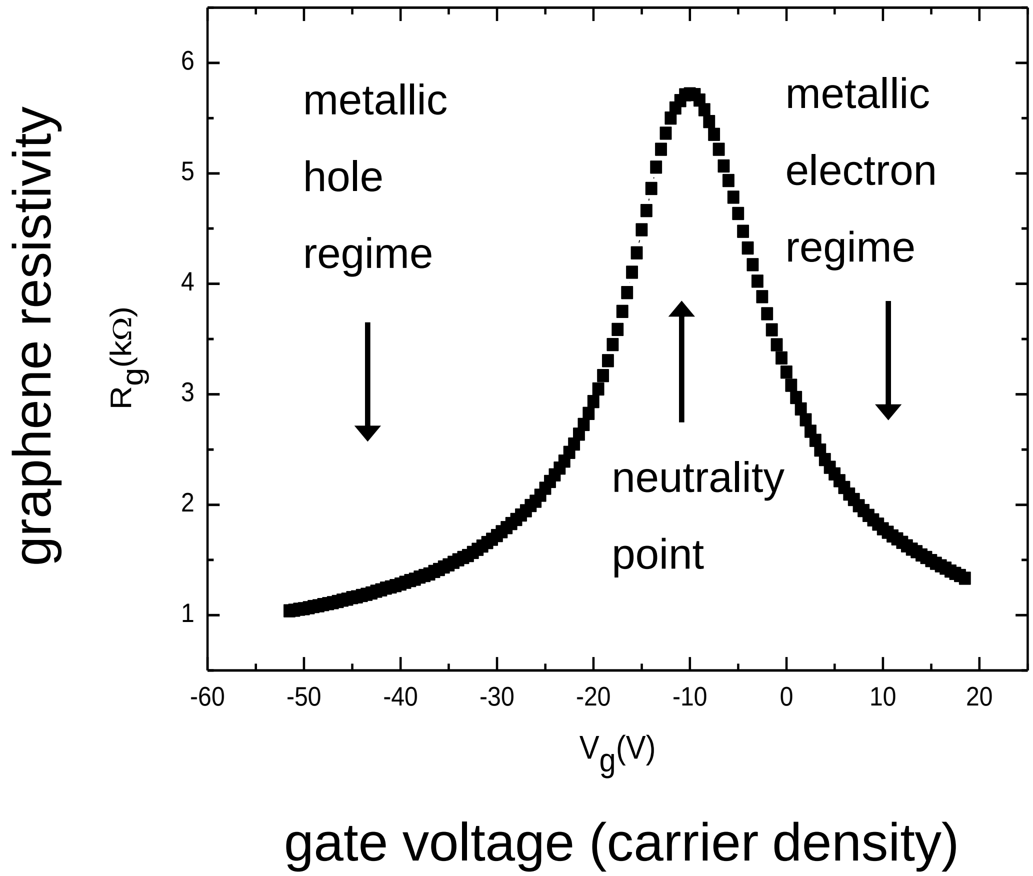
# Intermezzo: Solid state bandstructure and energy/momentum E(p) relation




Kinetic energy: $E=p^2/2m^*$ velocity $v=dE/dp$ $m^*$: effective mass

Semiconductors: $m^*$ positive for electron states/negative for hole states

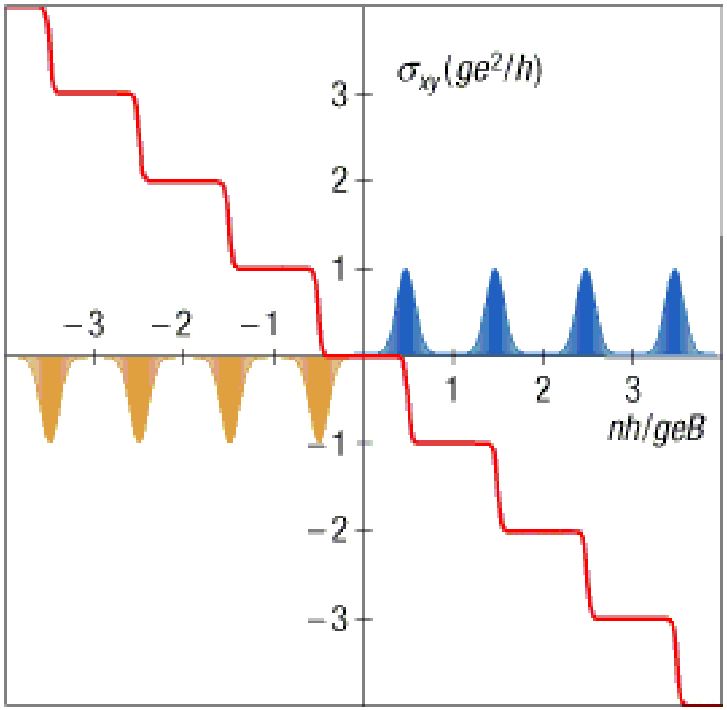
# Electron transport in graphene



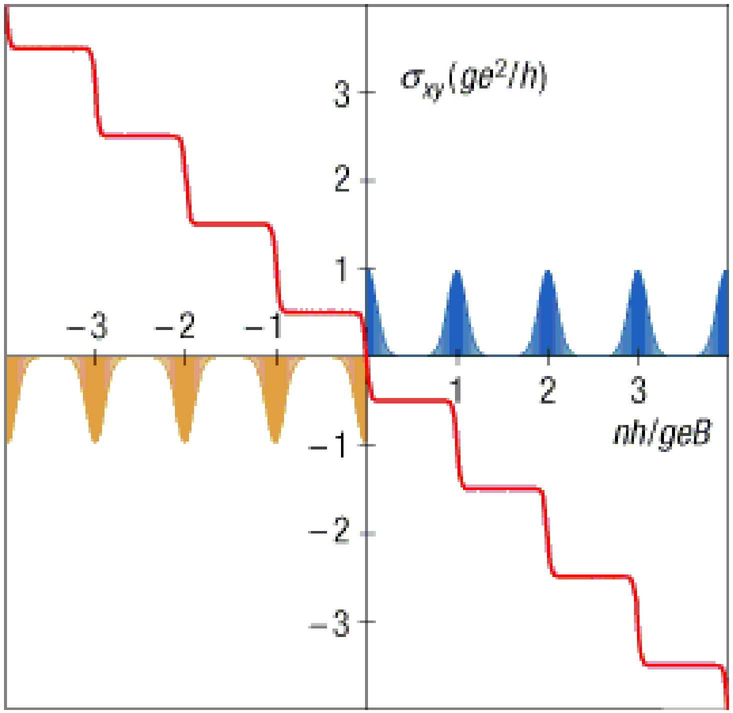

But similar behaviour for multilayer graphene/graphite!

# Anomalous Quantum Hall effect

Conventional semiconductor



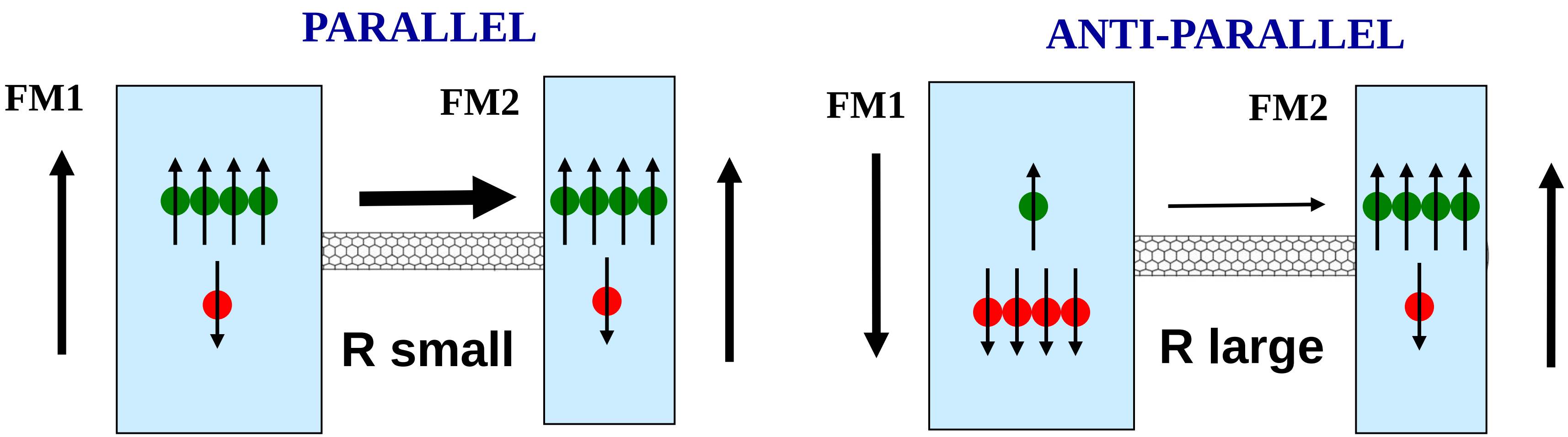

Single layer graphene

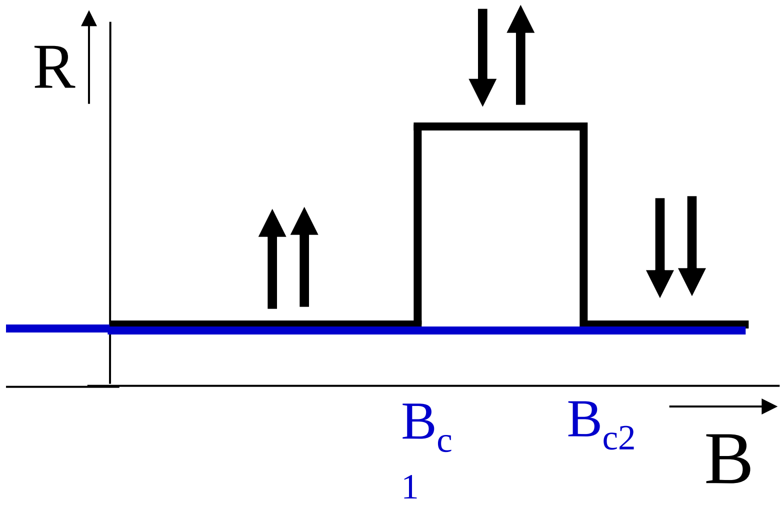


# Combination of “low tech”and “high tech” Zernike Nanolab Groningen


Electron beam lithography

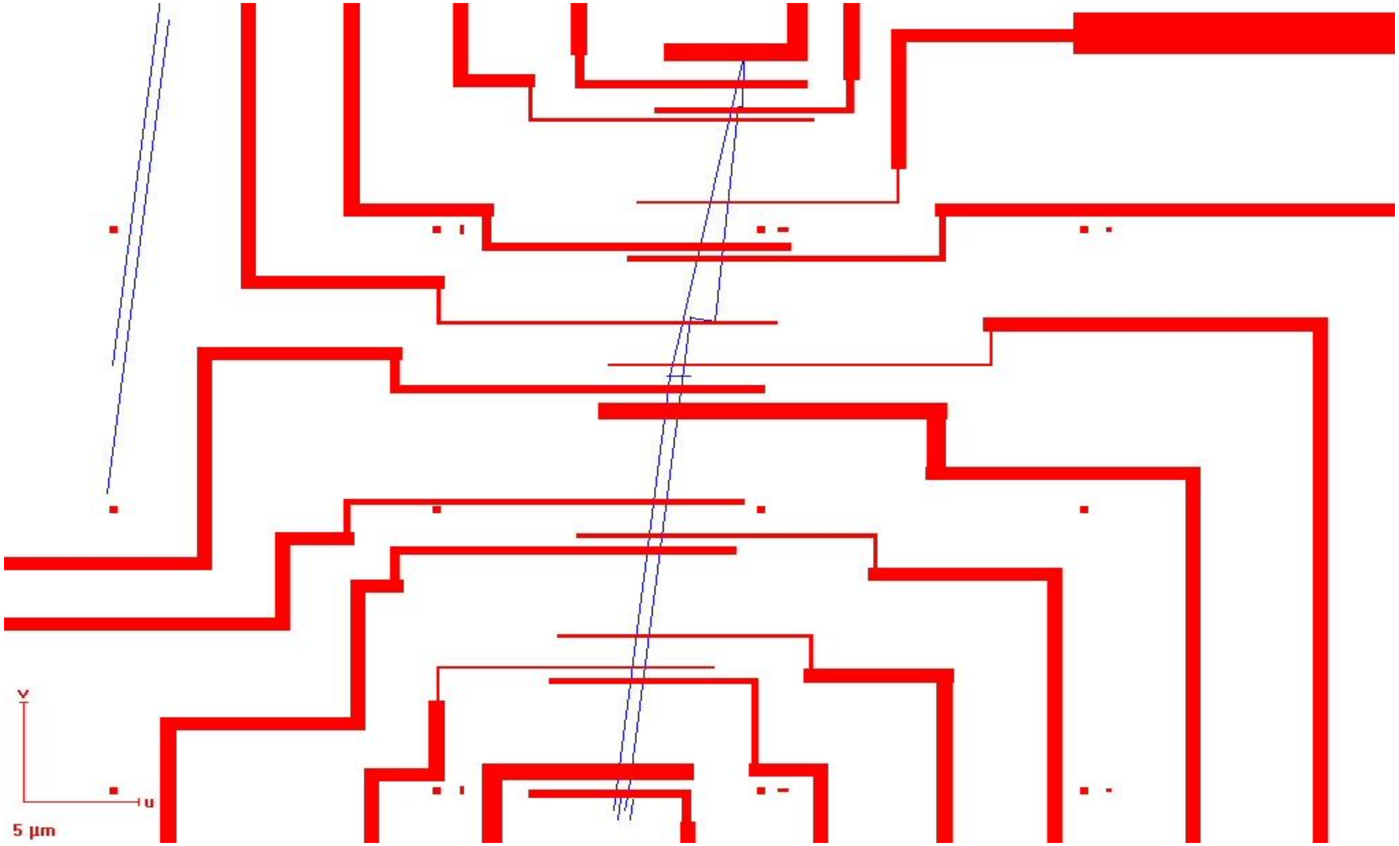
# Two-terminal spin valve



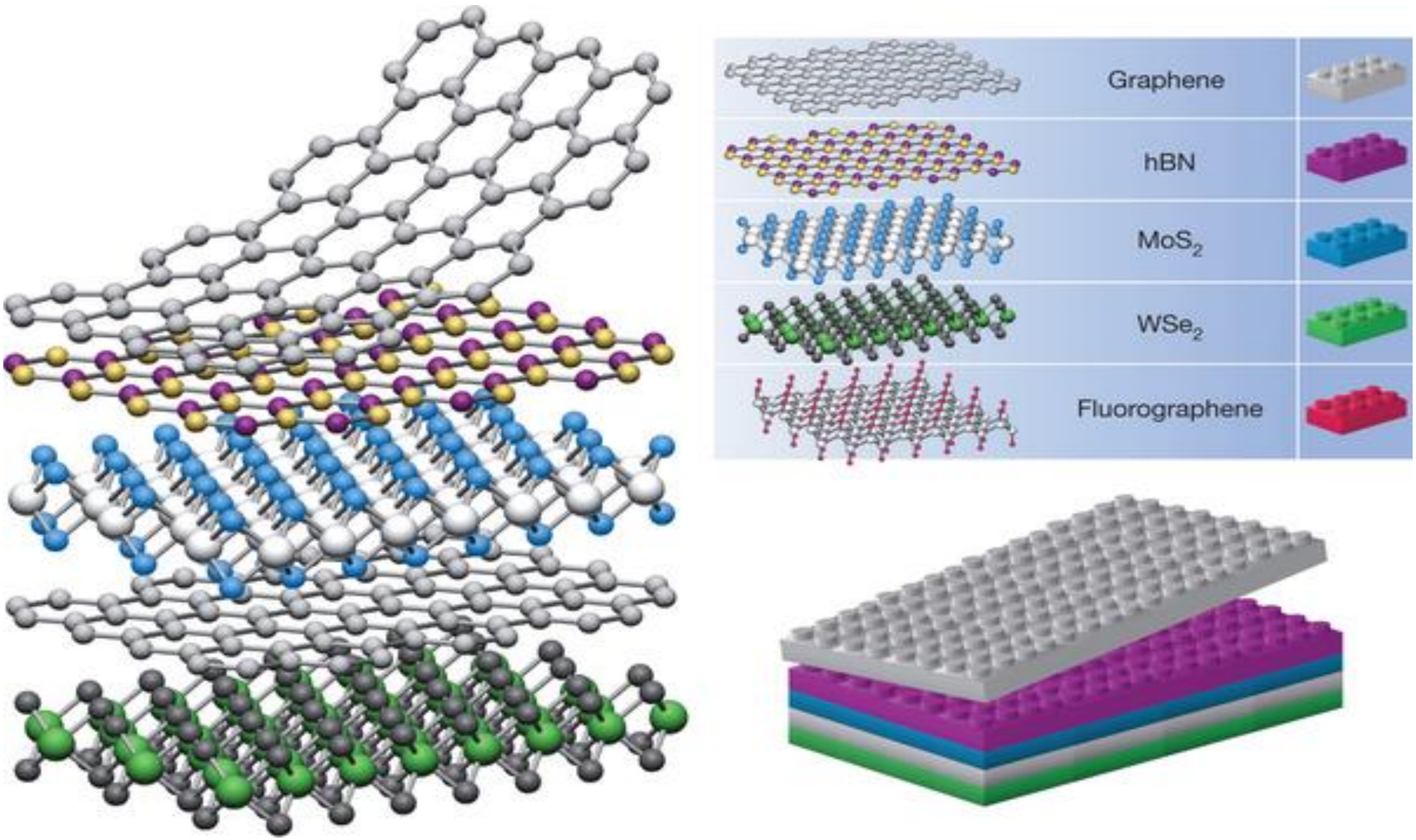



# Ferromagnetic contacts to graphene flakes

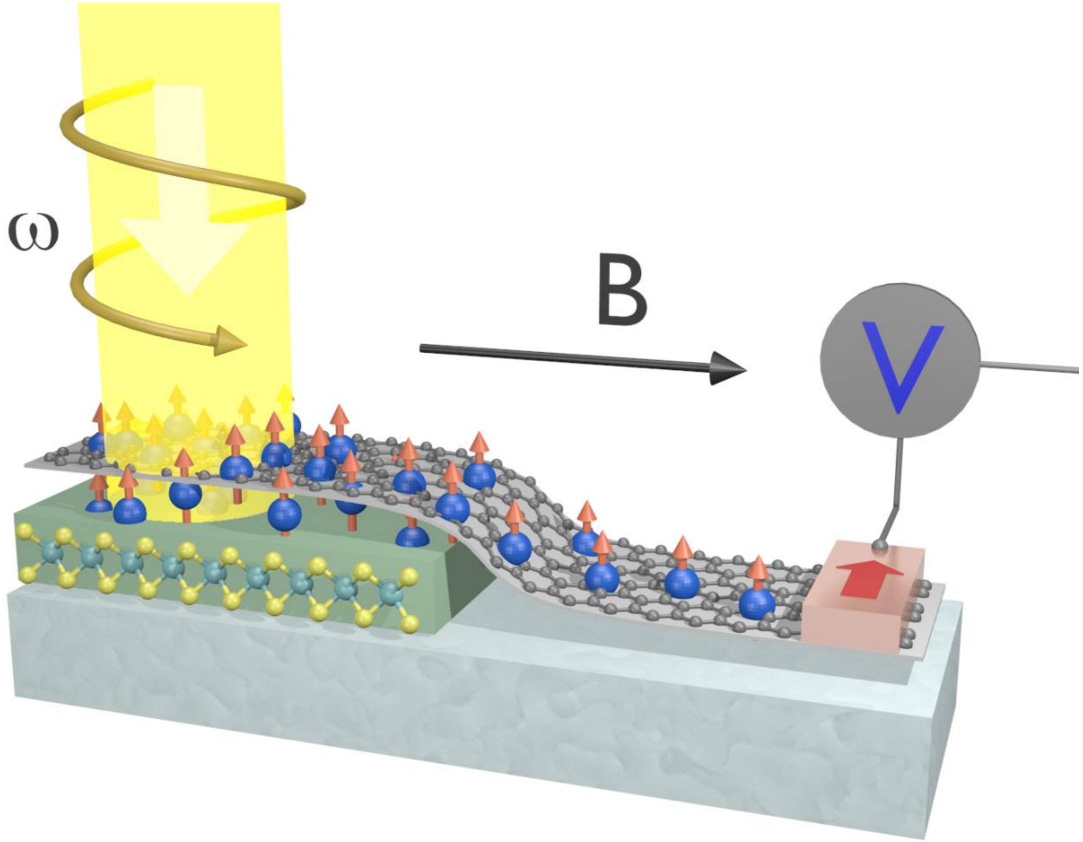
## Electron beam lithography



# Van der Waals materials and devices



# Towards new spintronics applications




GRAPHENE FLAGSHIP

Spintronics Work Package

# Engineering your DIY graphene transistor !!

You need:

Household foil


Graphite


Cotton wool

Multimeter

1) Make the gate first: Cover one side with graphite (rub out wel)

2) Cover other side with graphite (rub out ever better)

3) Measure resistance (it must be 10 kΩ or more)

4) Apply a DC voltage  between back and front of the foil (caution!)

5) Voila!  Your home made graphene transistor is ready!  Congratulations!