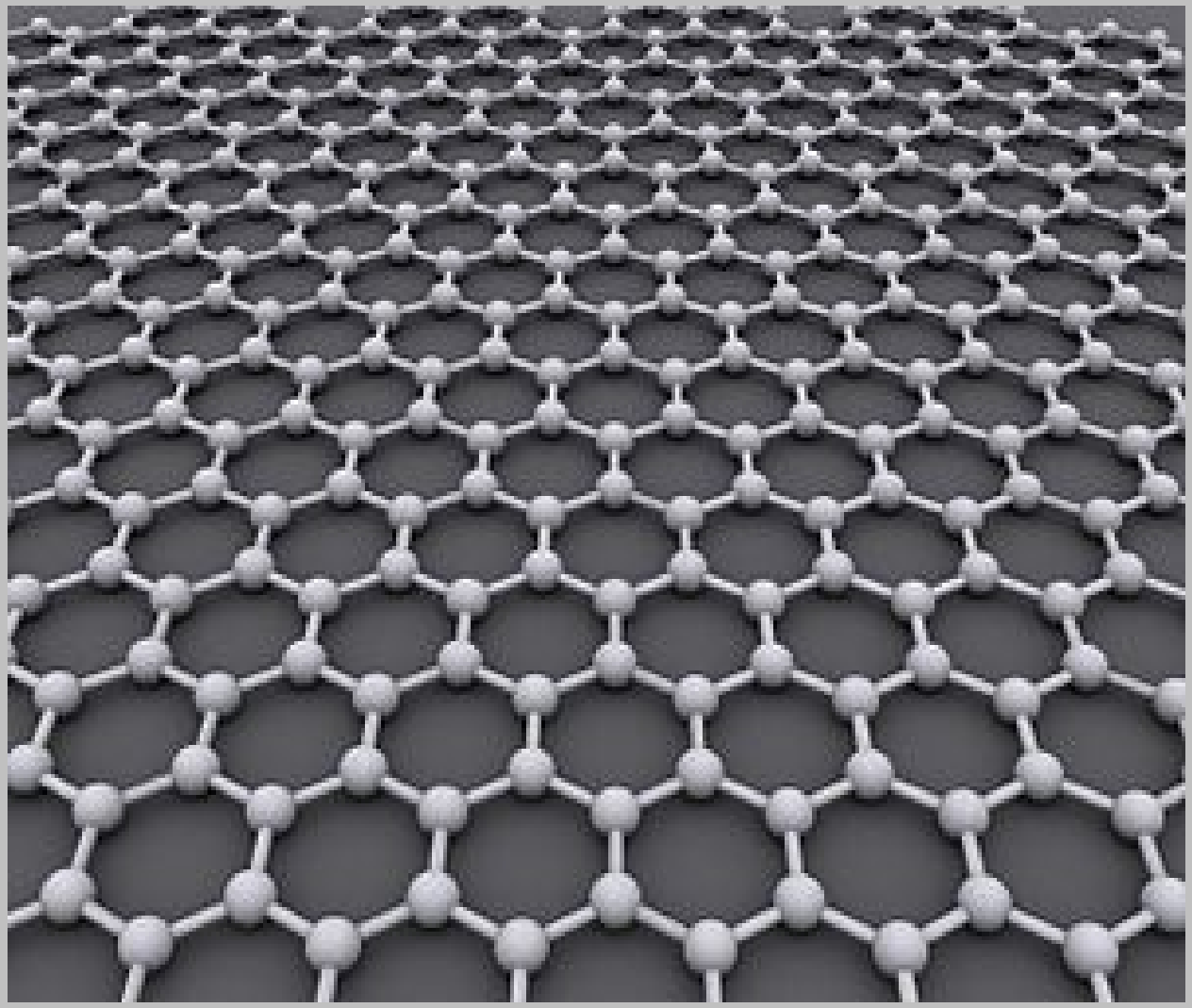
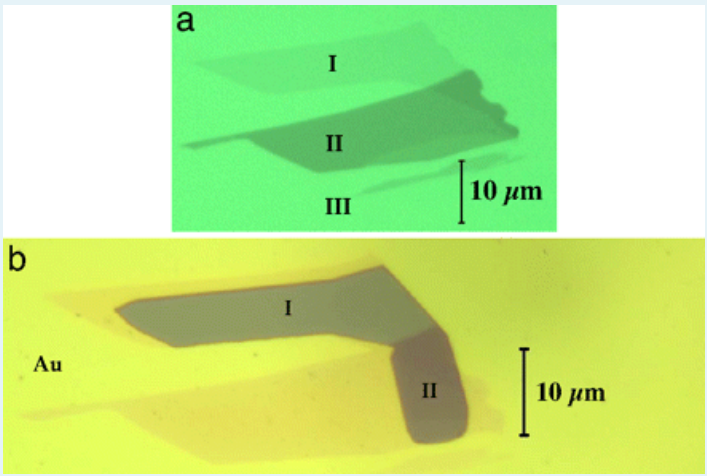
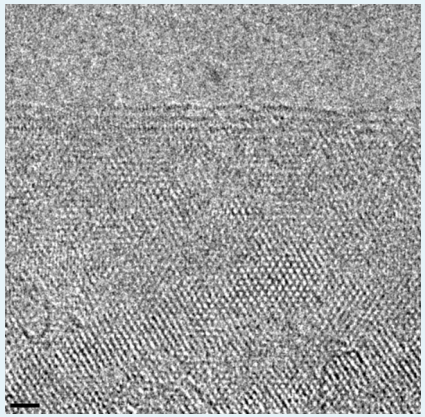
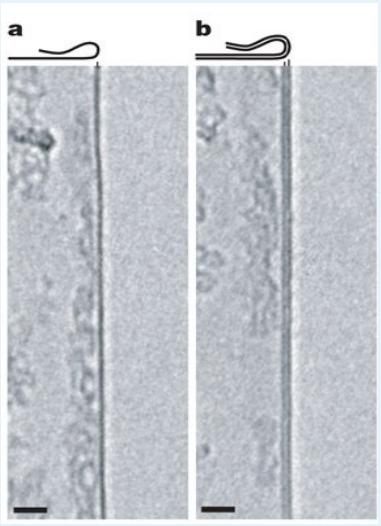
Graphene: a 2D world



Really?







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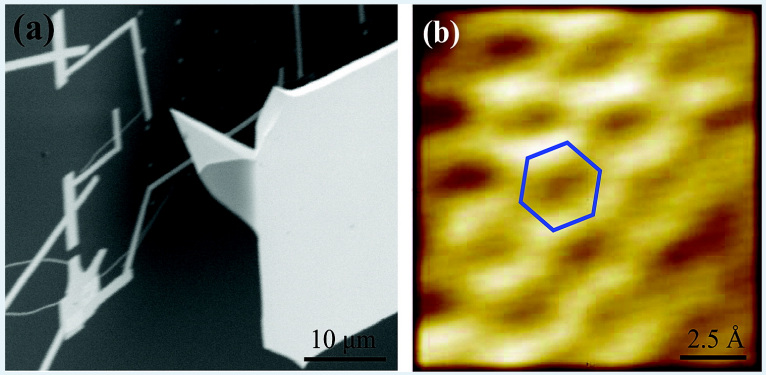
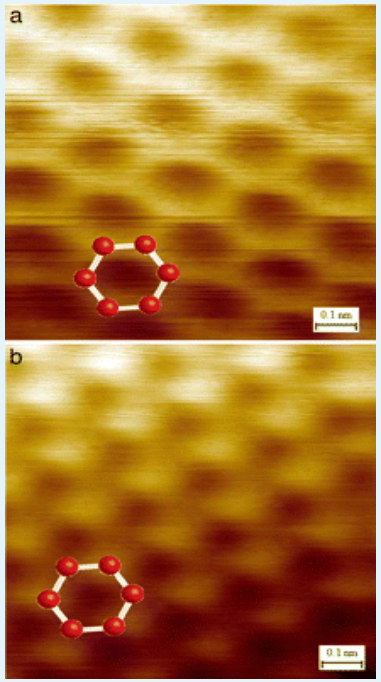
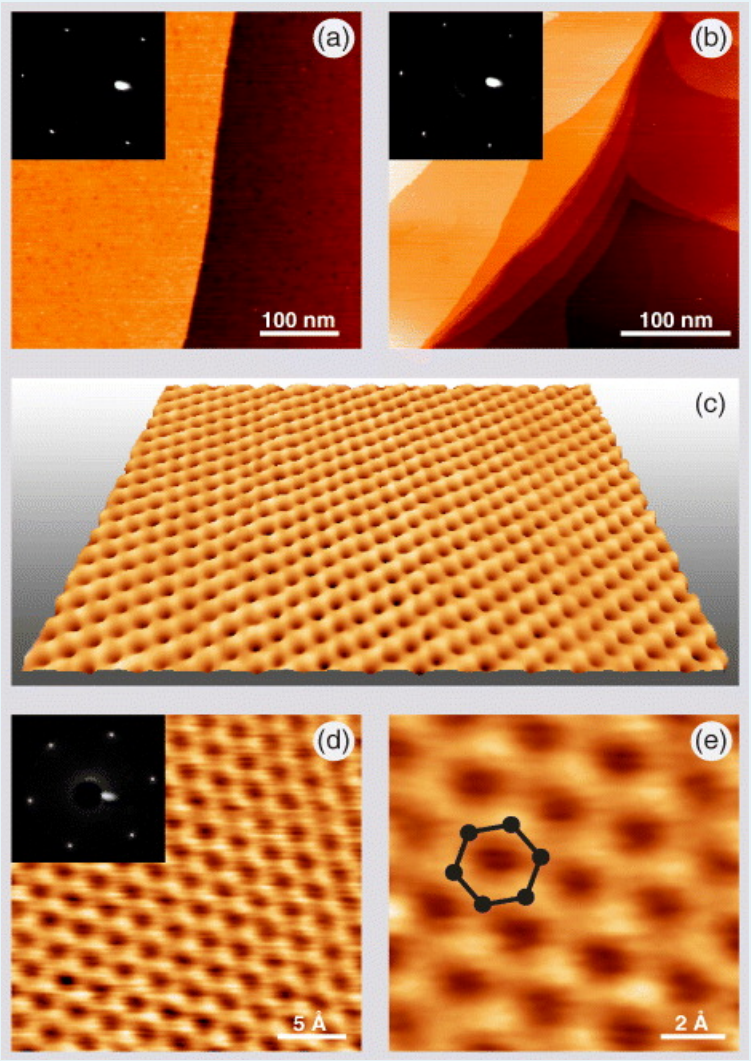
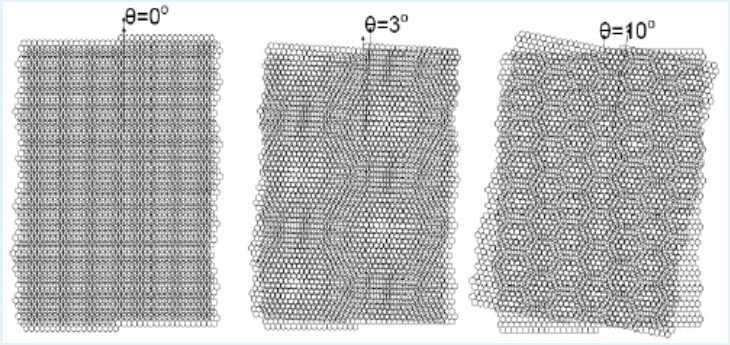
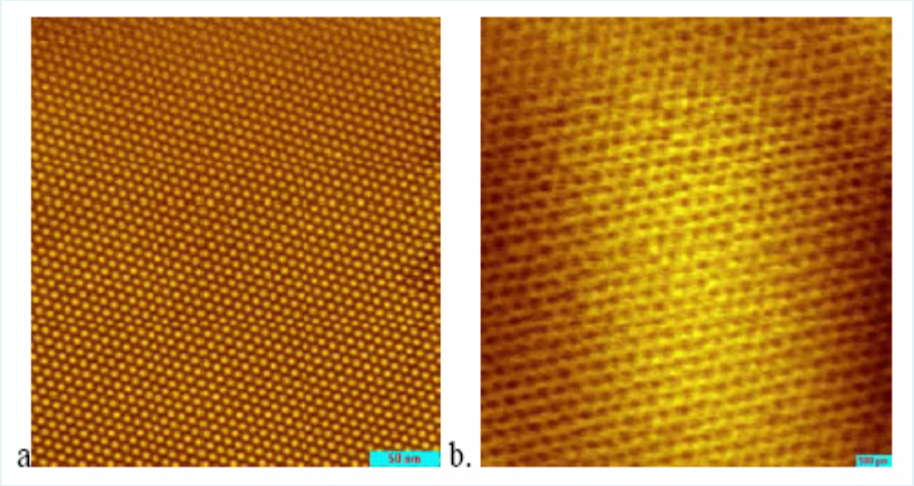


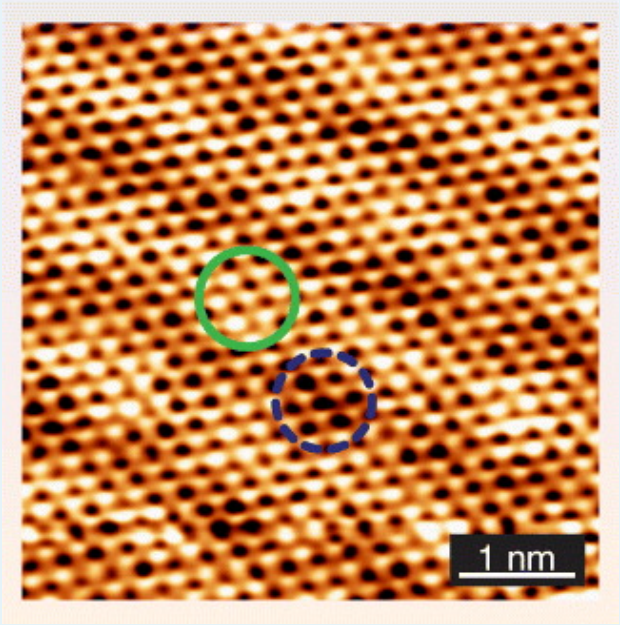


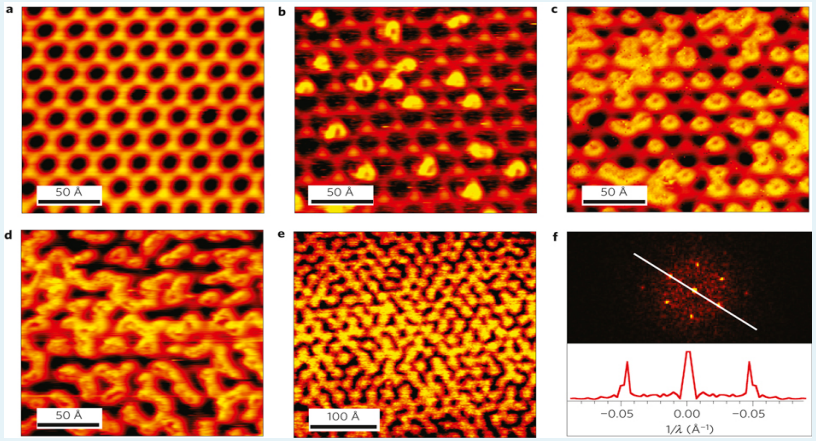


Really?

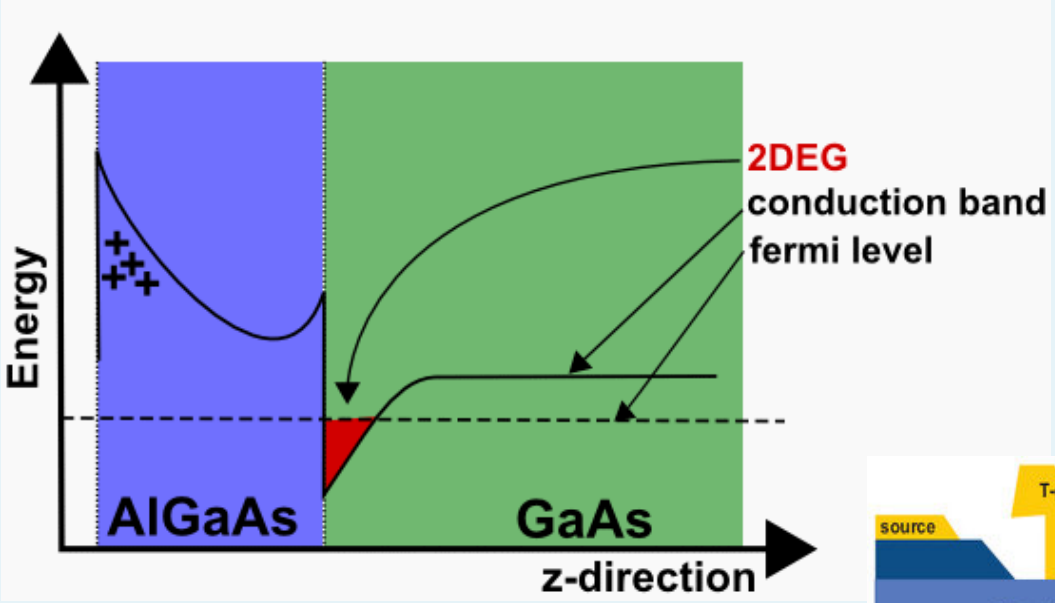


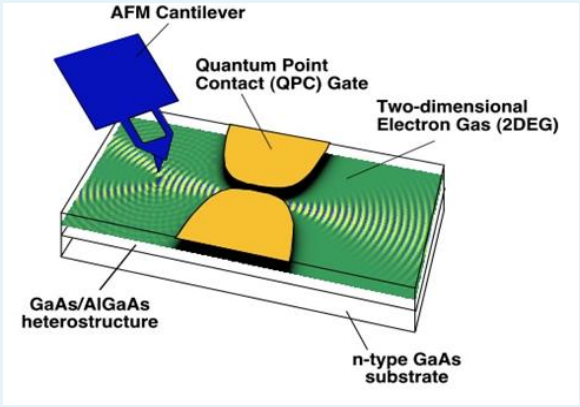


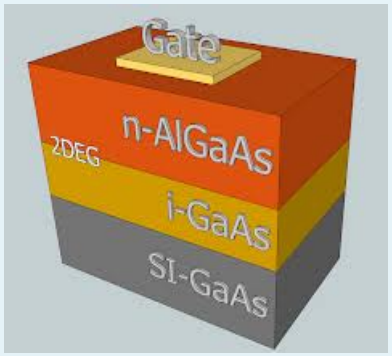


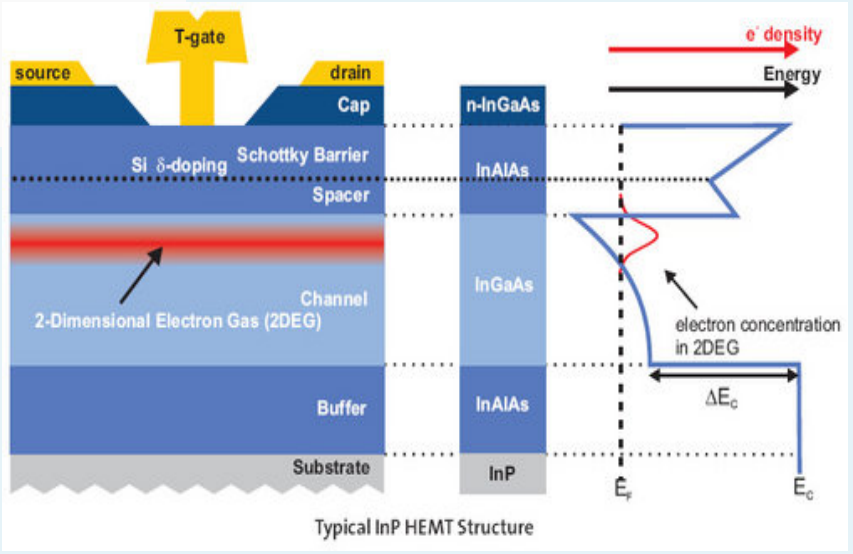


Traditional 2DEGs



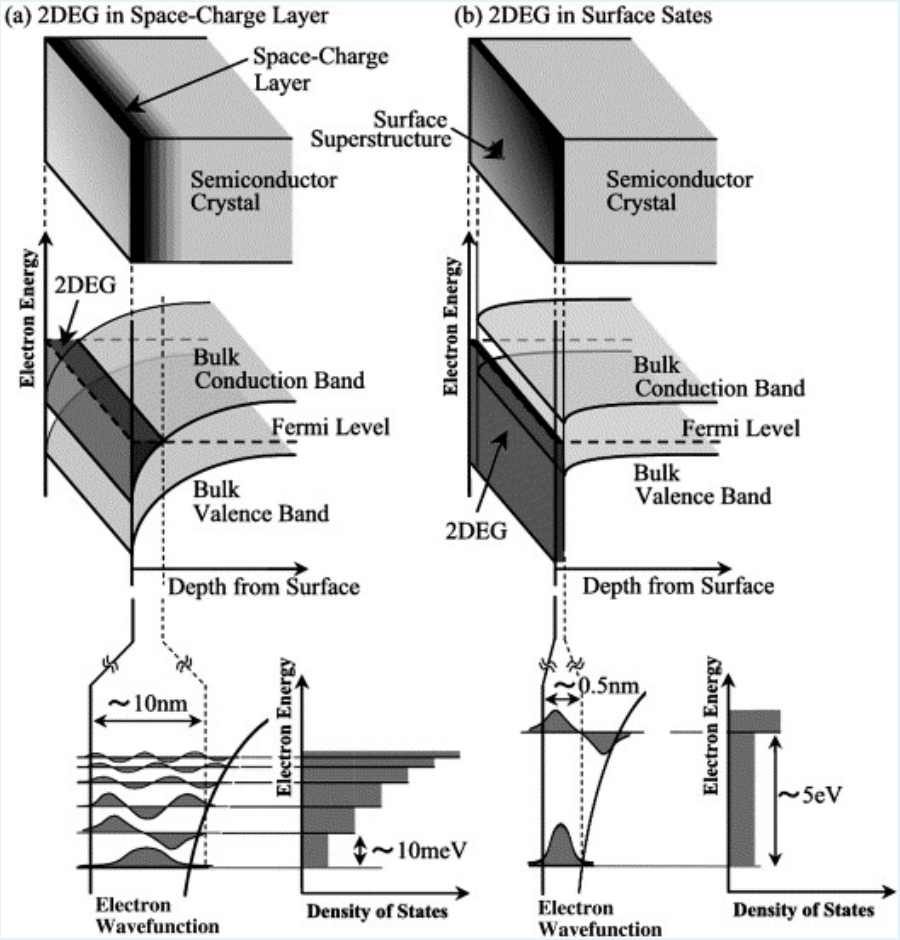


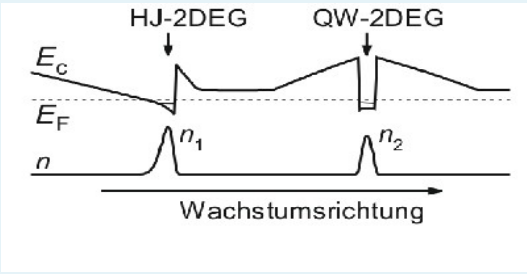




Typical InP HEMT Structure

Traditional 2DEGs

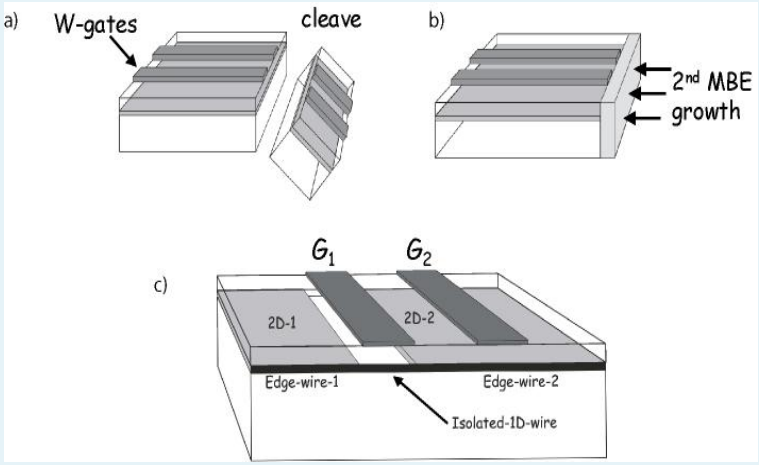


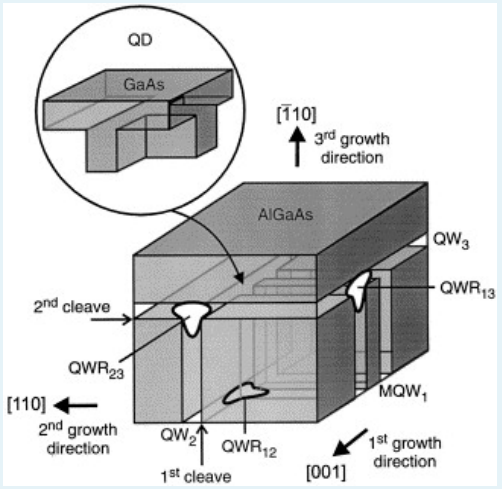


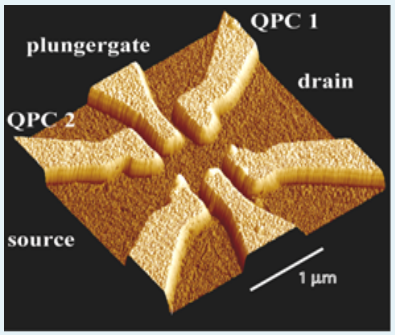
Explore **quantum mechanics** in mesoscopic systems:

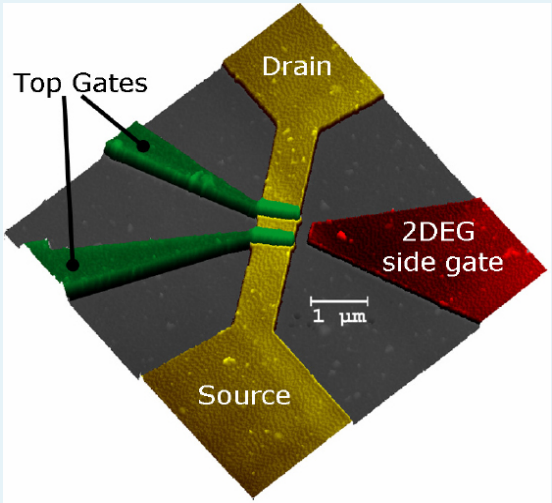
- quantized motion perpendicularly to the growth direction
- free motion in the plane

Traditional 2DEGs

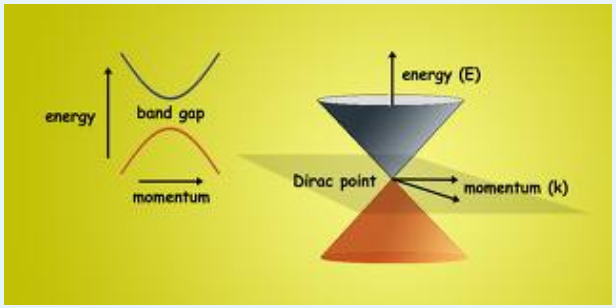








Electronic structure



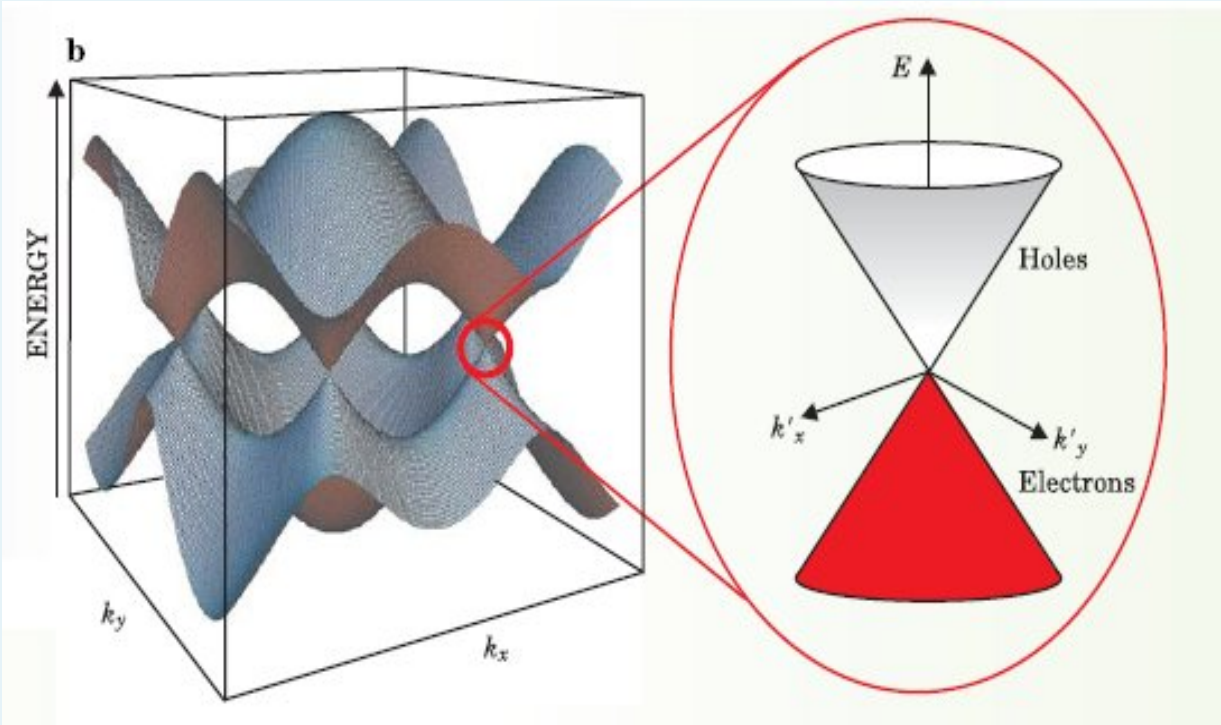
- E *vs* k is linear close to the special points K,K'
- “pseudospin” parallel or antiparallel to k

Close to K,K'

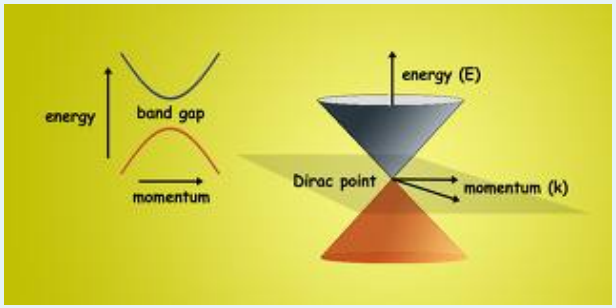
$E = \hbar v_F k$

$N(E) \mu \pi k_E^2$

$n(E) \mu E$



Electronic structure



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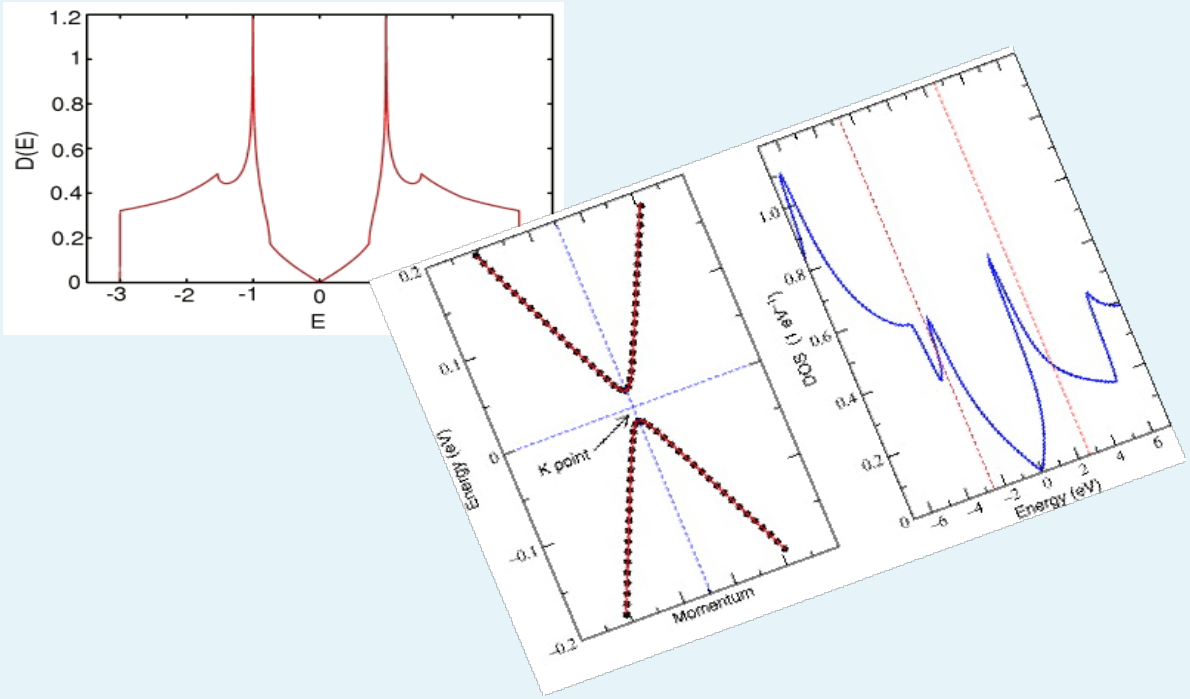
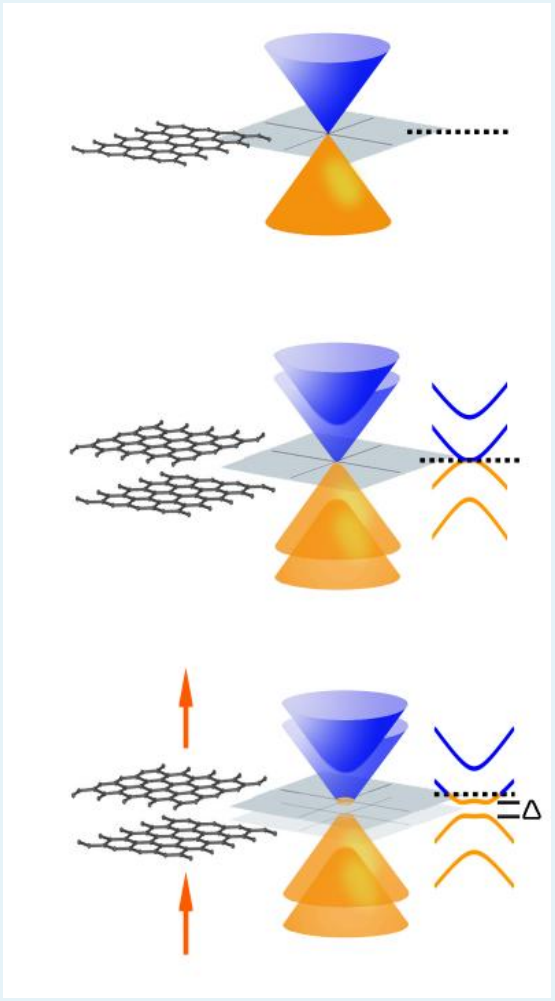
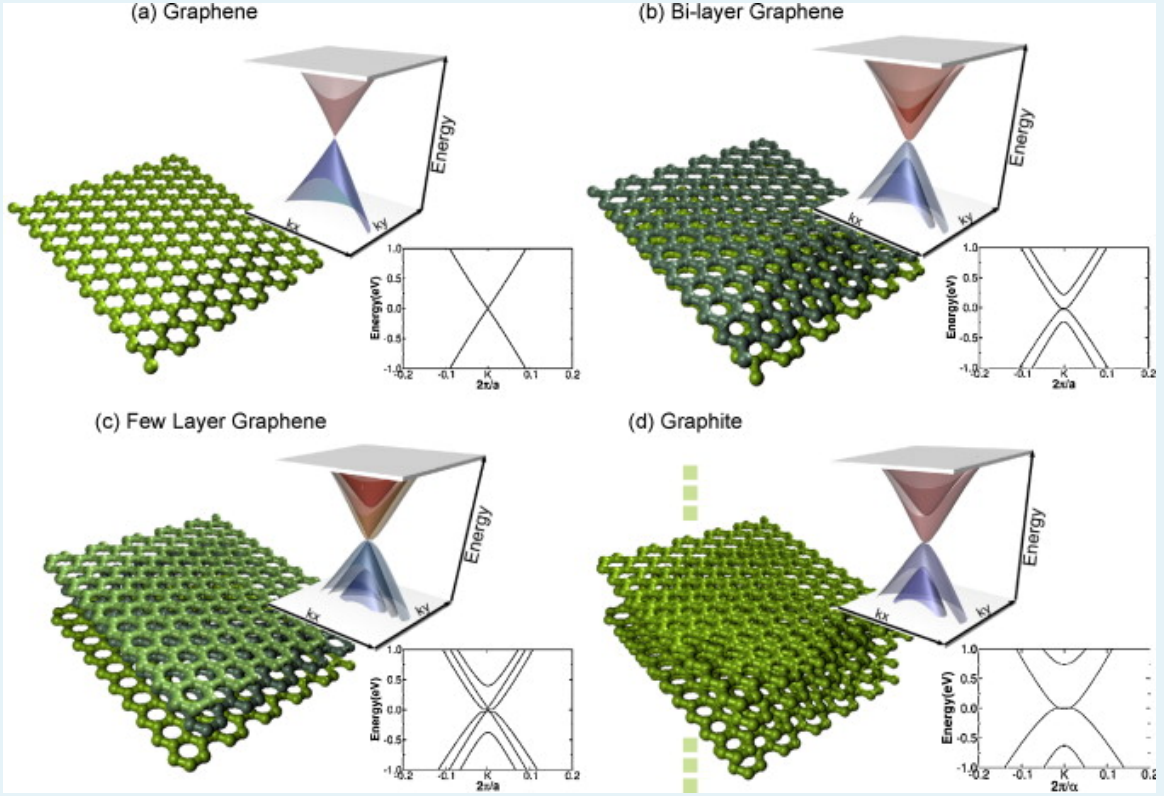
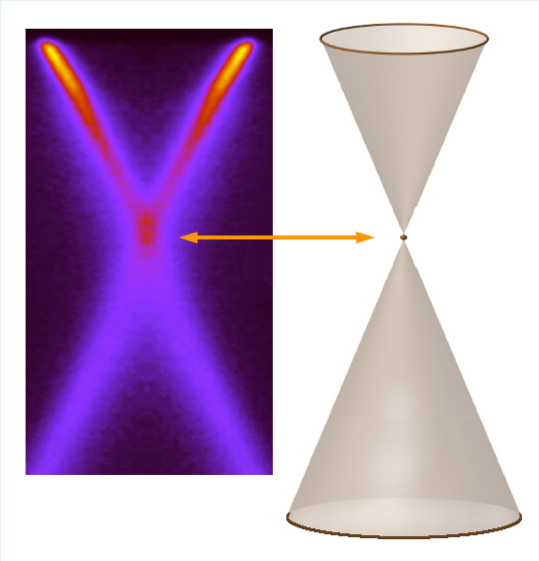


Electronic structure

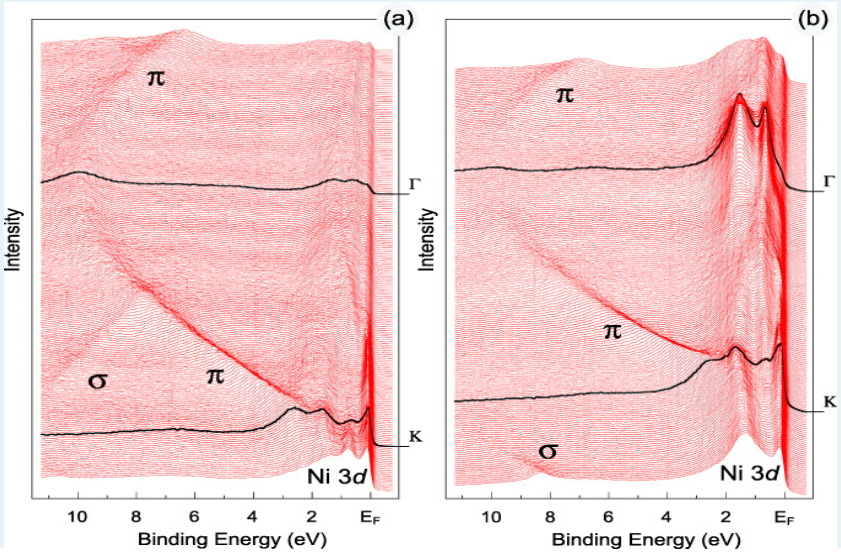


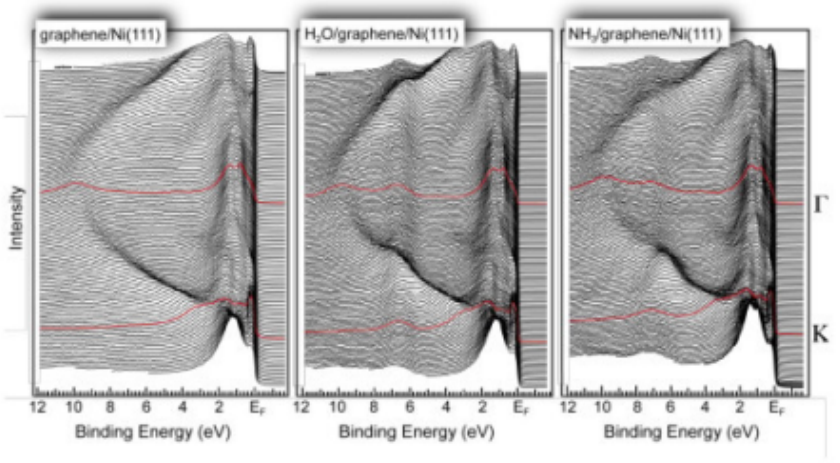


Electronic structure

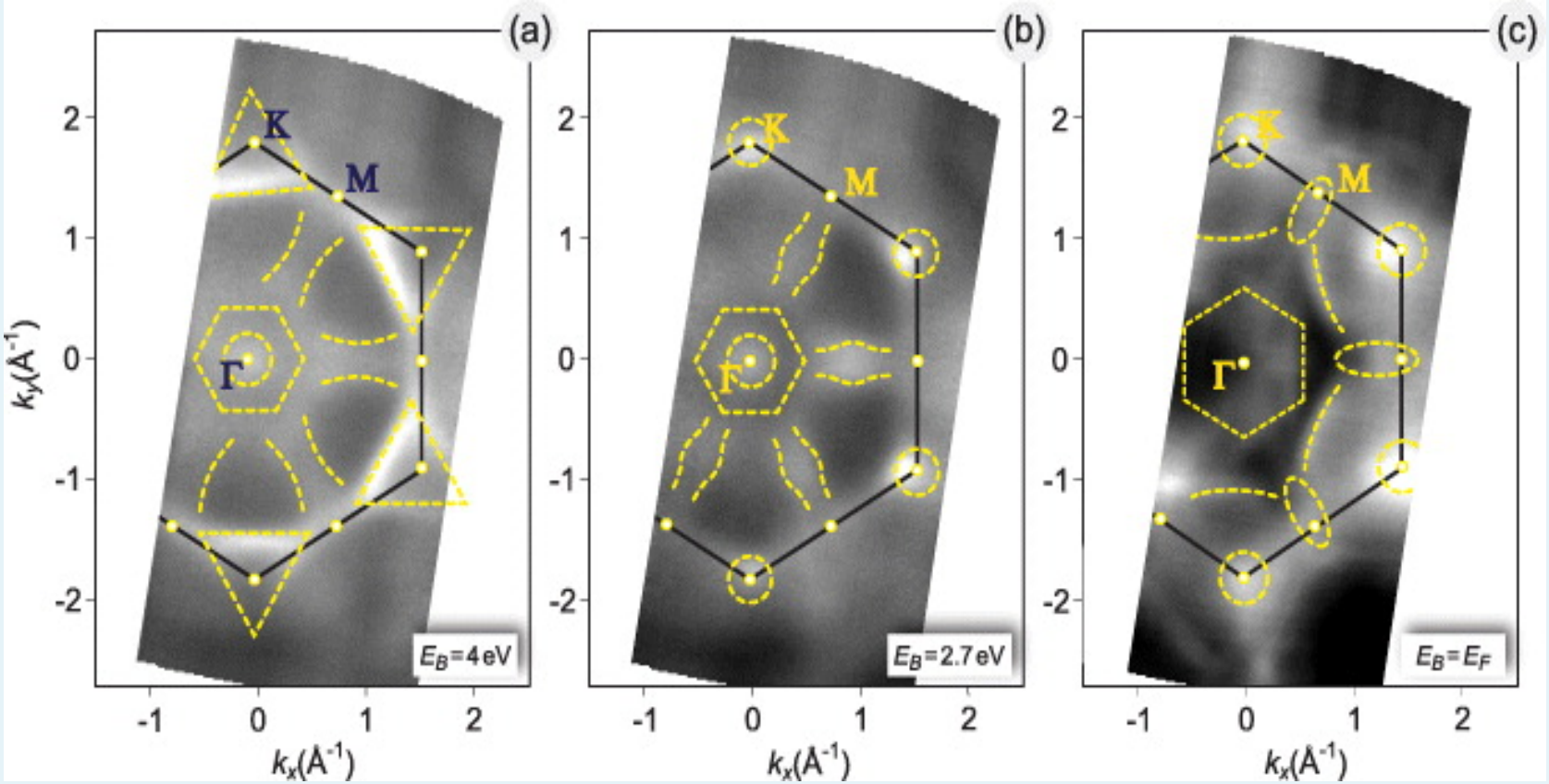


ARPES measures I(E,k)

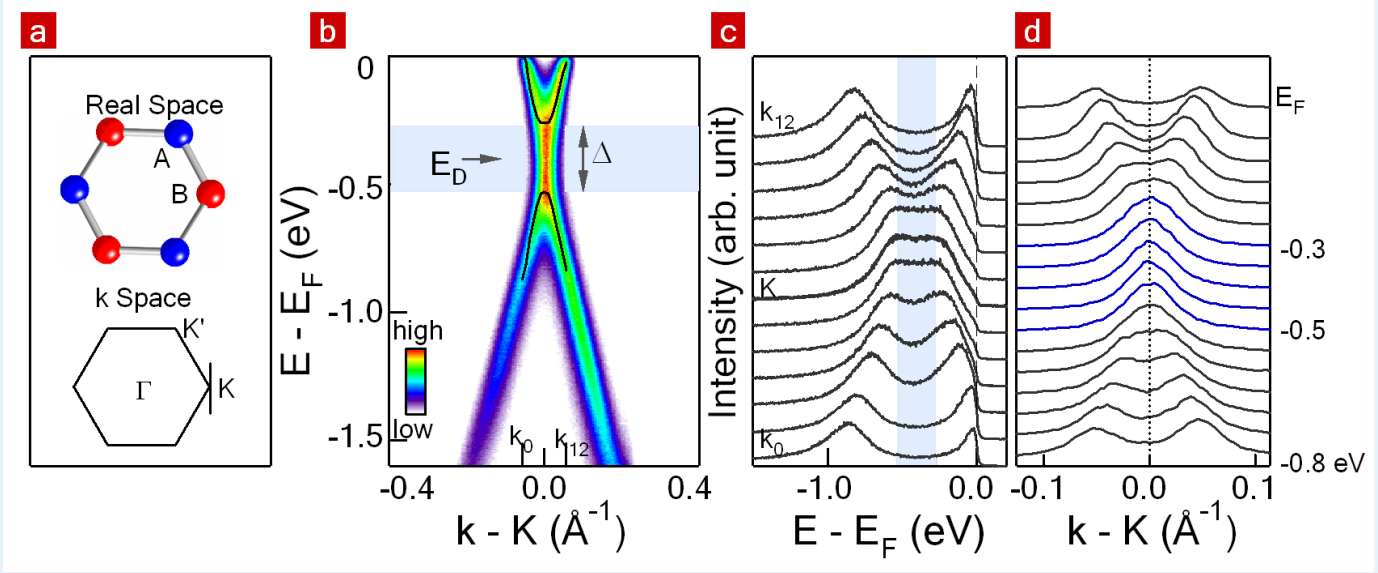


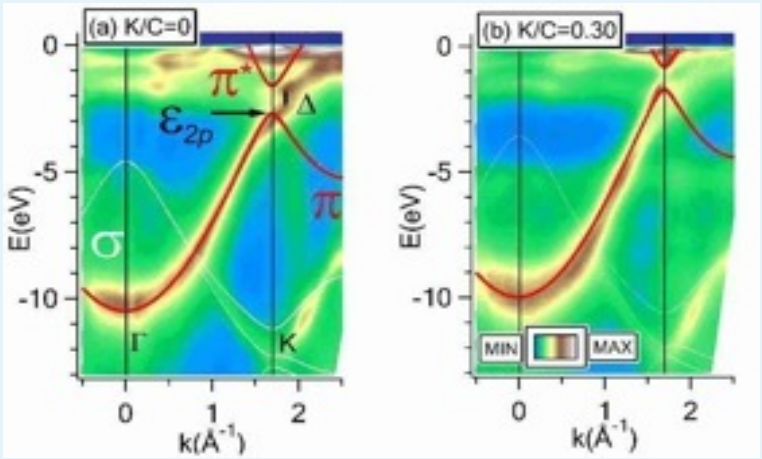


Electronic structure

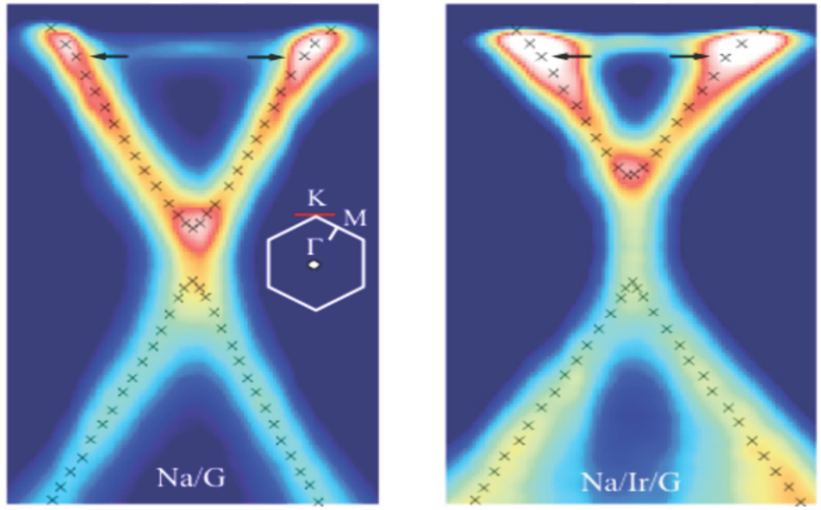


Electronic structure

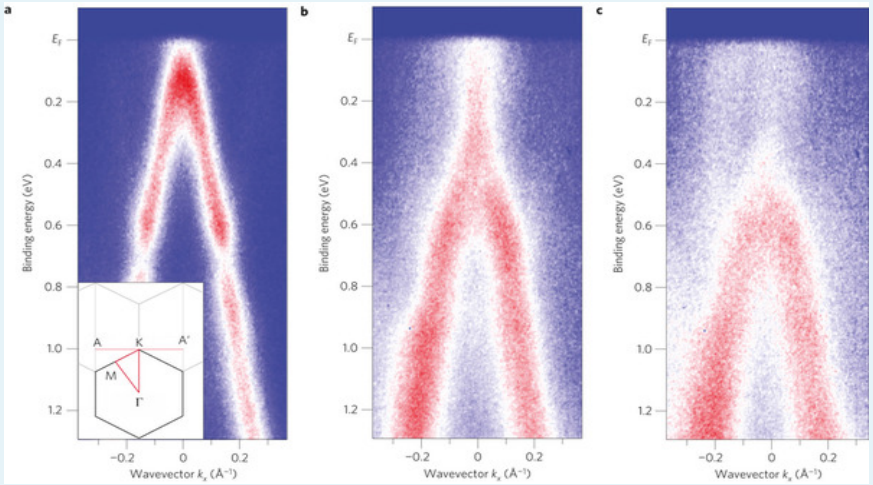




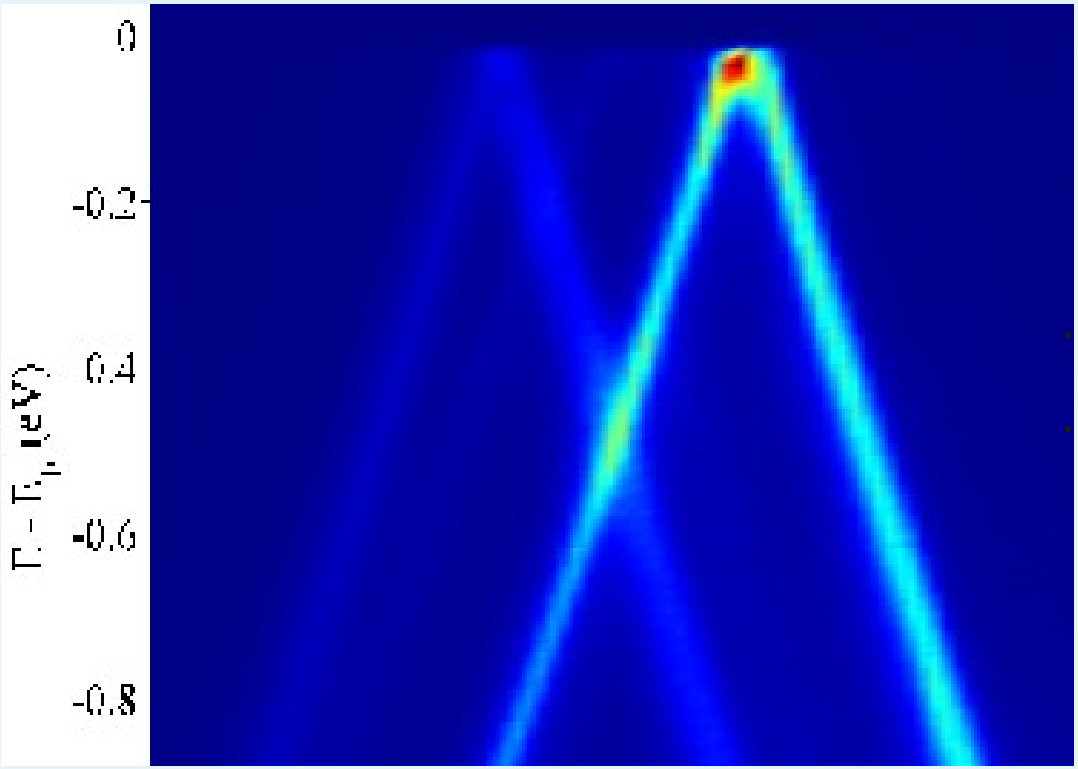
Electronic structure



Gap opening, doping, electron scattering, etc. can be accurately investigated



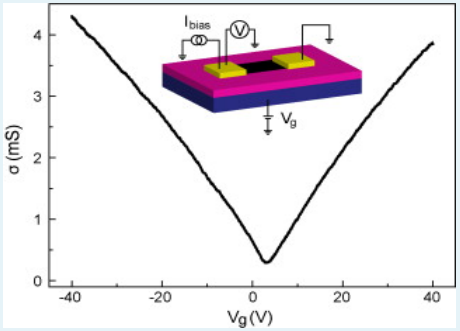
Electronic structure

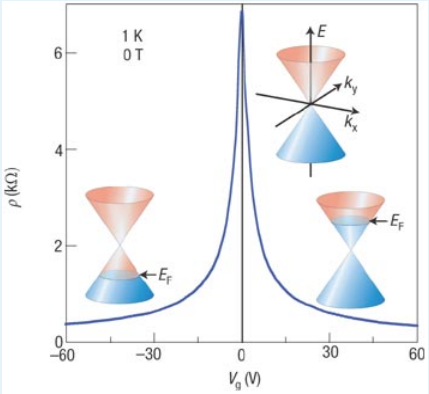


Uncoupled graphene layers:

Multi Layer Graphene

Transport properties

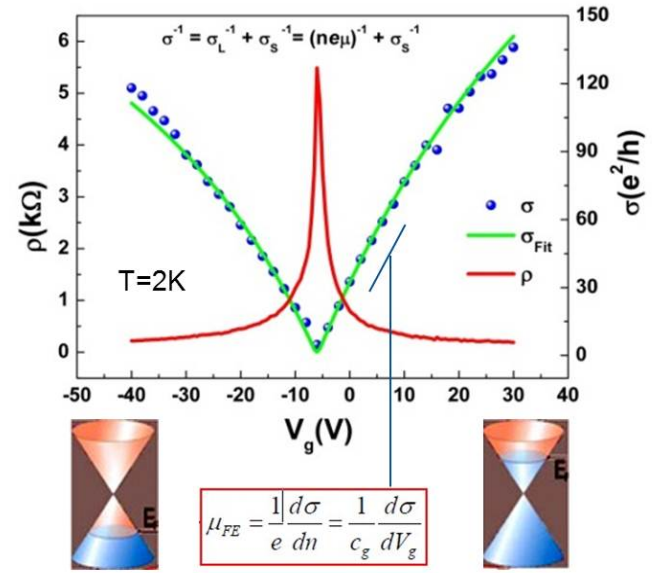




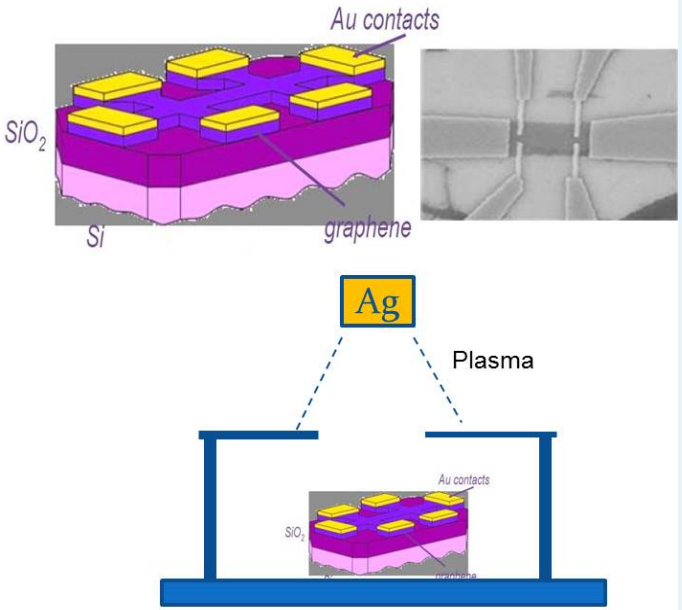
- electric field effect
- ambipolar conduction

$$n = C_i V_g$$

$$C_i = \varepsilon A/t$$

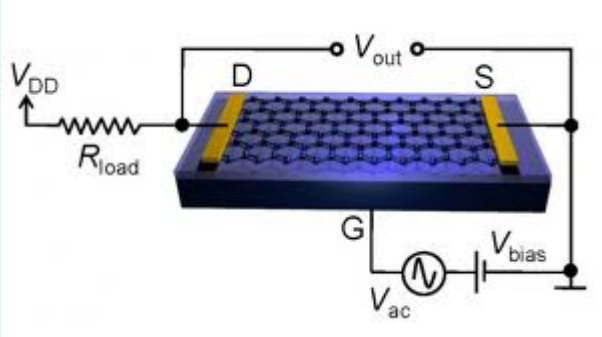


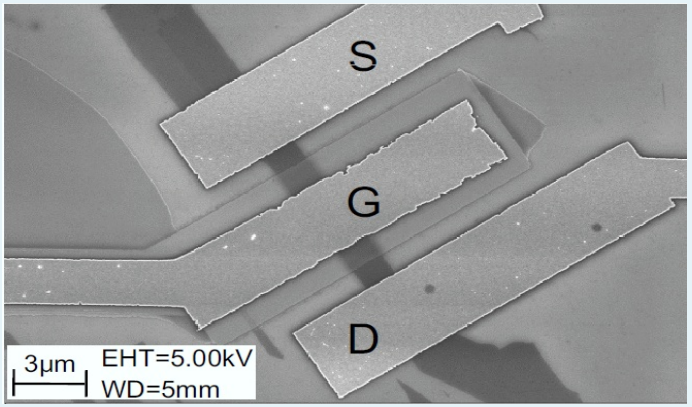
Electric Field Effect in our Graphene

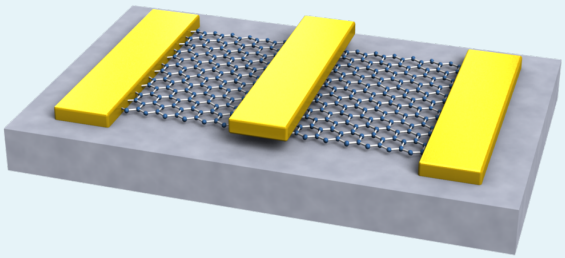


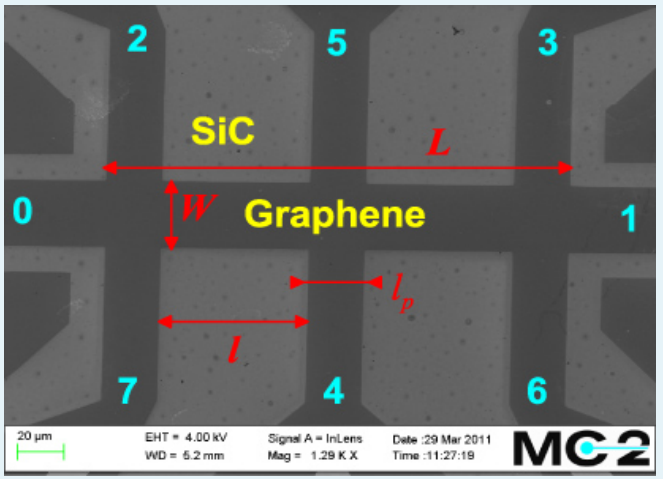
Ag cluster deposition

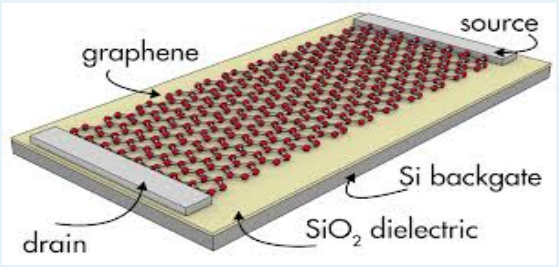
Transport properties



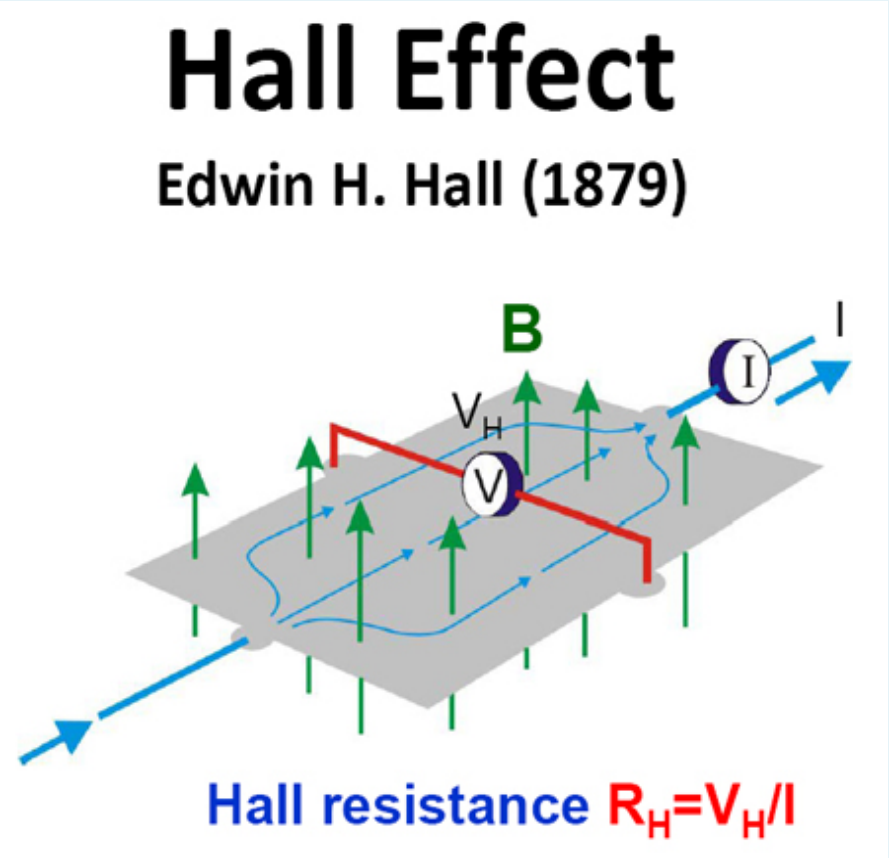


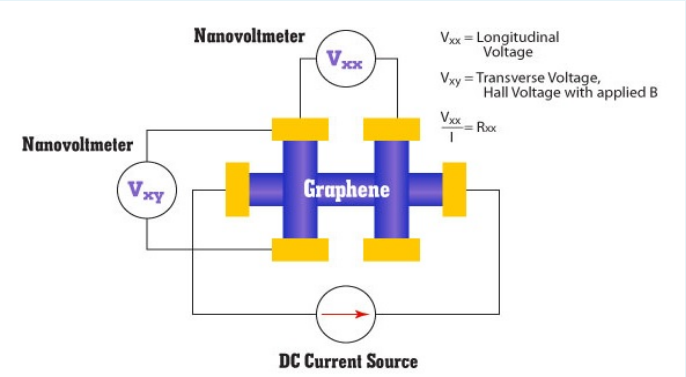






Transport properties

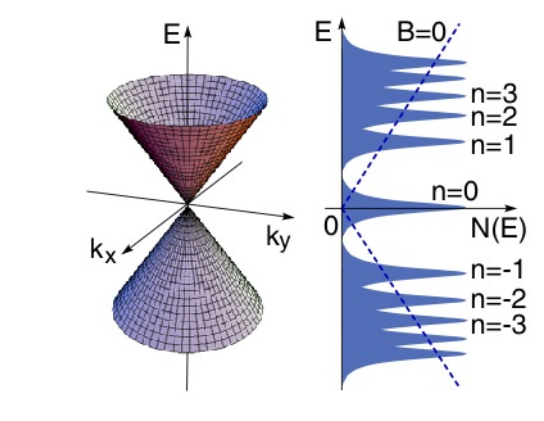




R_H / B allows to determine the *sign* of charge carriers

$r_H = - 1/n|e|c$

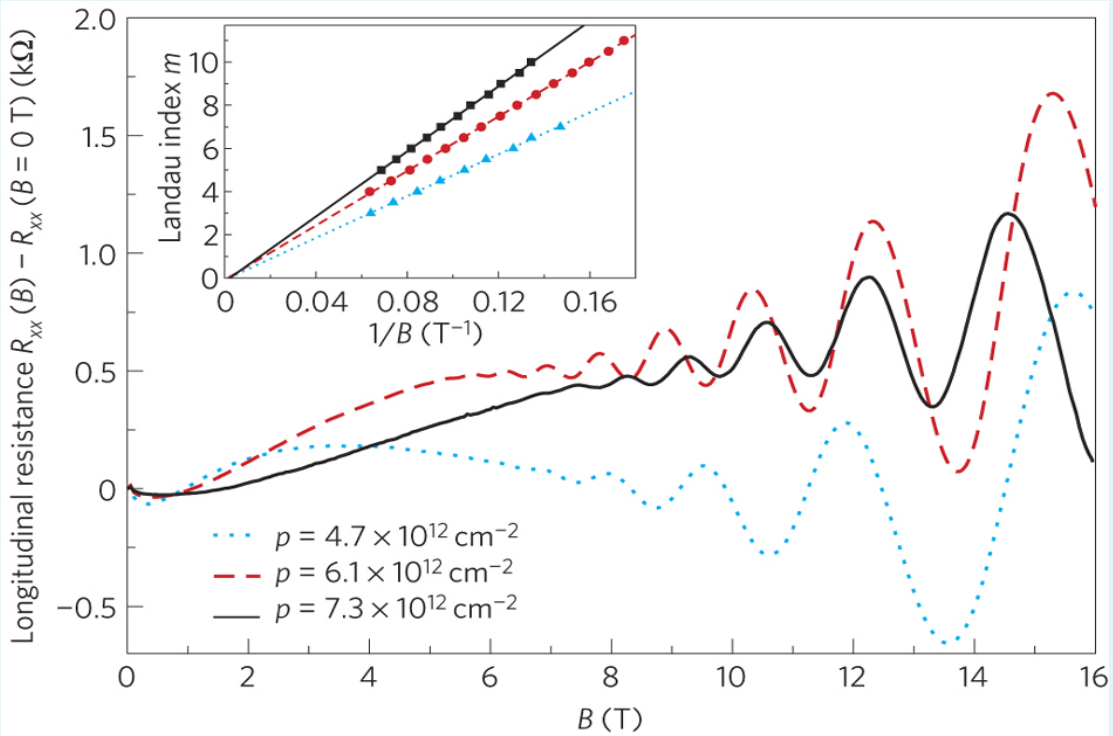
Transport properties



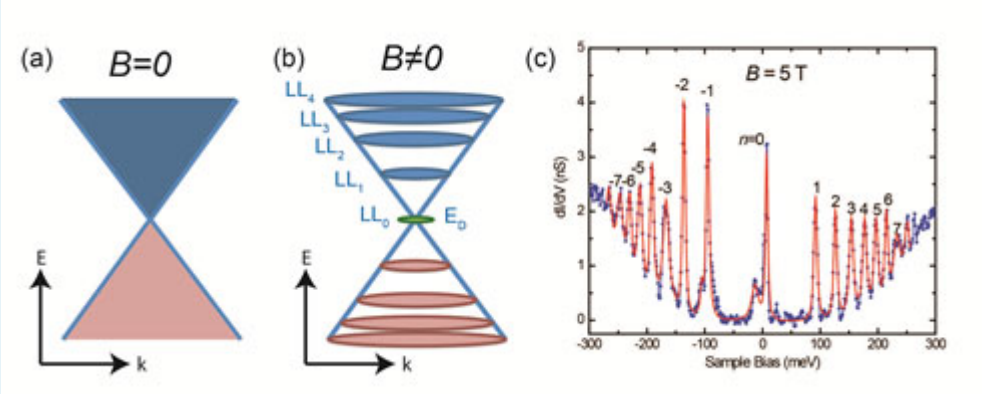
Well-defined **Landau levels** develop when increasing B..

..and cause

Shubnikov - de Haas oscillations in the longitudinal magnetoresistance

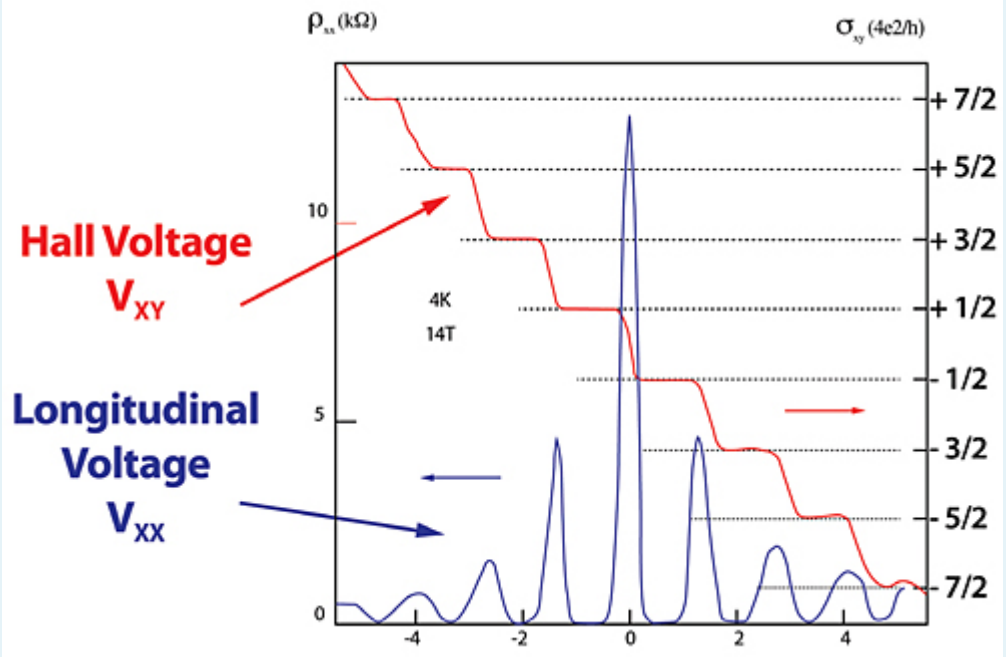


Transport properties

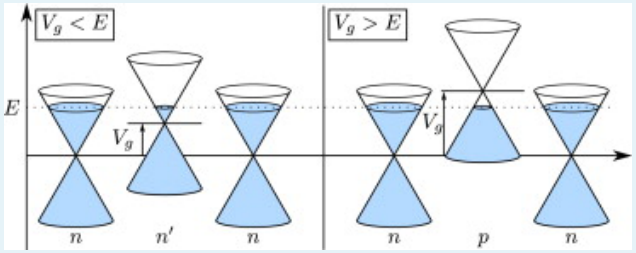


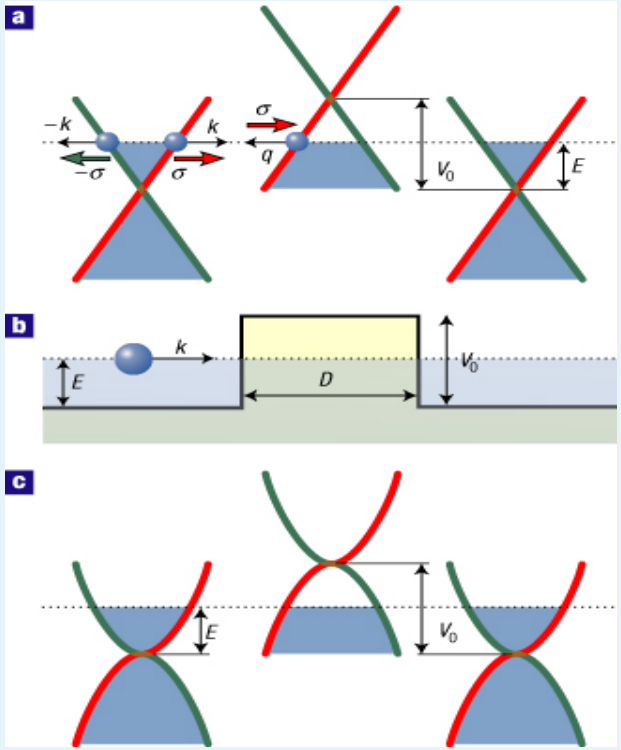
..ultimately, at very high fields,

Quantum Hall Effect



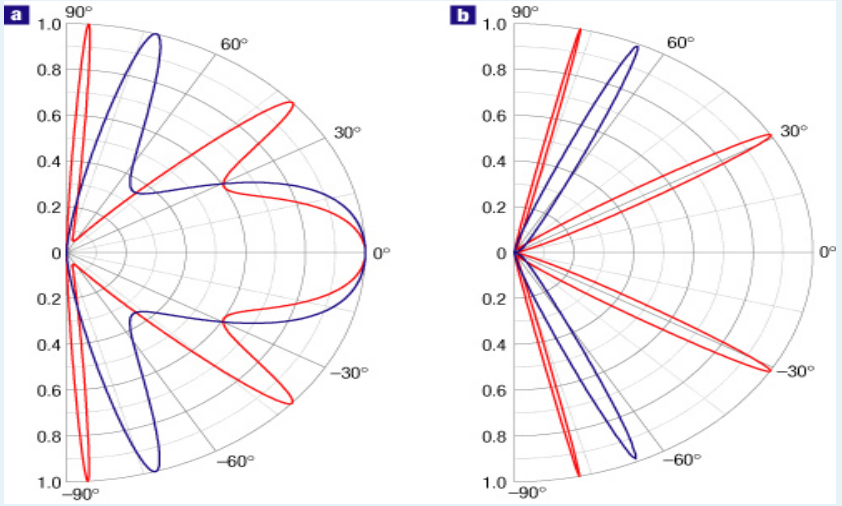
Transport properties



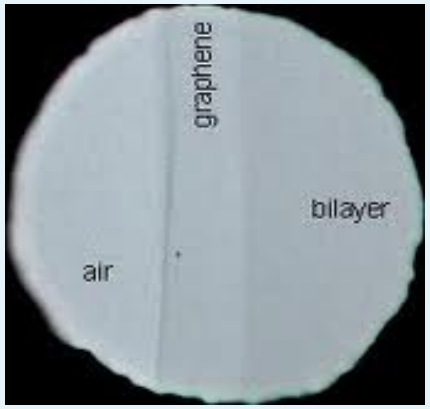


Klein tunneling is related to negative kinetic energy:

- evanescent waves for ordinary electrons
- freely propagating (hole) waves for Dirac electrons

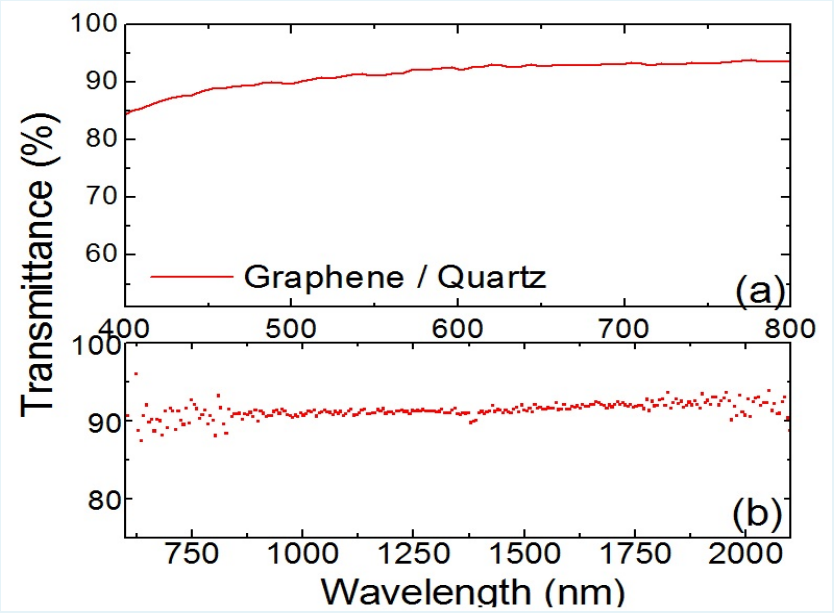


Transport properties



Photons and Dirac fermions obey similar *E vs k* relations,

$1-T=\pi\alpha \cong 0.03$



- $A = A_0 \exp(i\omega t)$
- $\tau^{-1} \mu A_0^2 \times n(\omega/2) \mu \omega$
- $W_{abs} \mu \omega^2$
- $W_{inc} \mu E^2 \mu A_0^2 \omega^2$

Notable transport properties

- Both *e* and *h* carriers can be injected – ambipolar FE
- Very high mobility – fast response to external fields
- High saturation velocities – good behavior up to high fields
- Room temperature Quantum Effects
- Transparent to light

...however

- lack of a band gap – no reliable swtiching properties

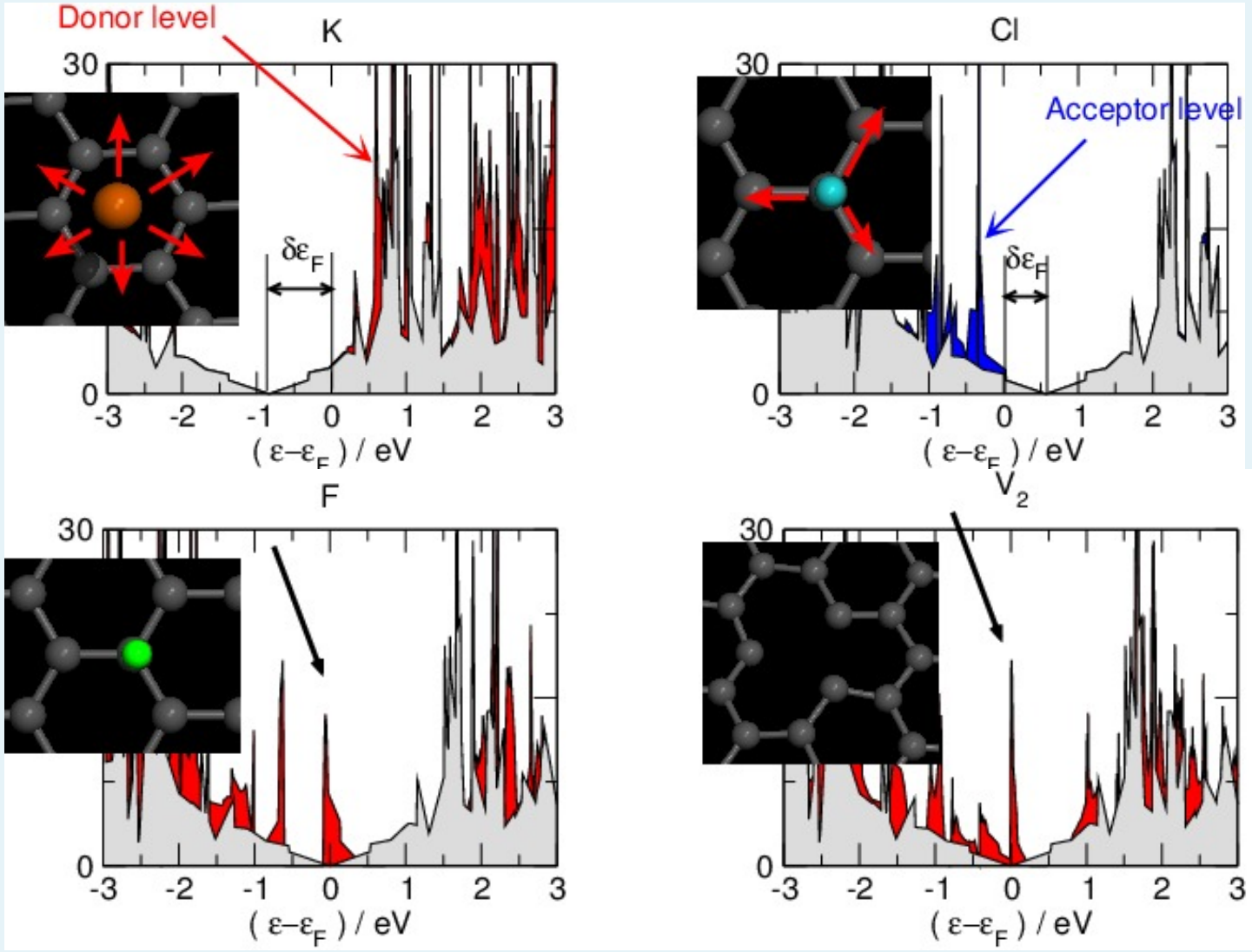
Further notable properties

- The thinnest possible material - only one atom thick
- The material with the largest surface area per unit weight – one gram of graphene can cover several football pitches
- The strongest material – 40 N/m, theoretical limit
- The stiffest known material - stiffer than diamond
- The most stretchable crystal – can be stretched as much as 20%
- The most thermal conductive material - ~5000 Wm-1K-1atroomtemperature
- Impermeable to gases – even for helium

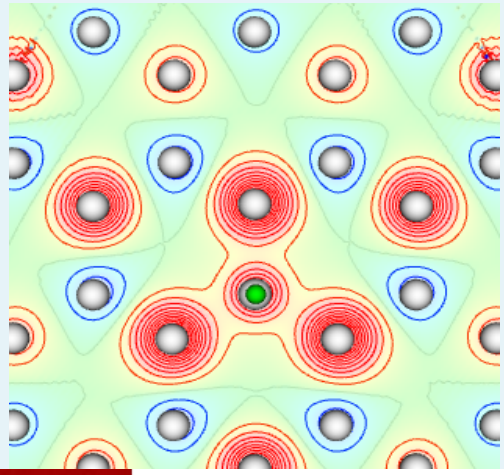
Atomic-scale defects

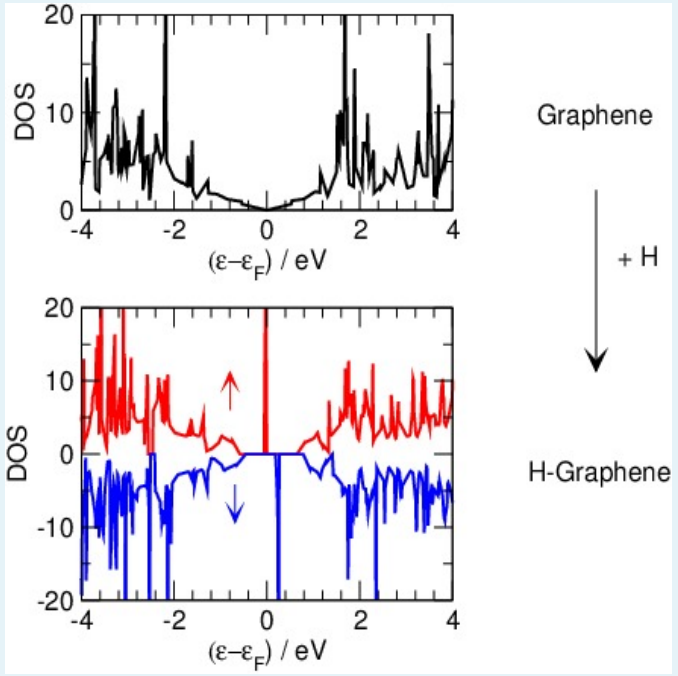
ionic

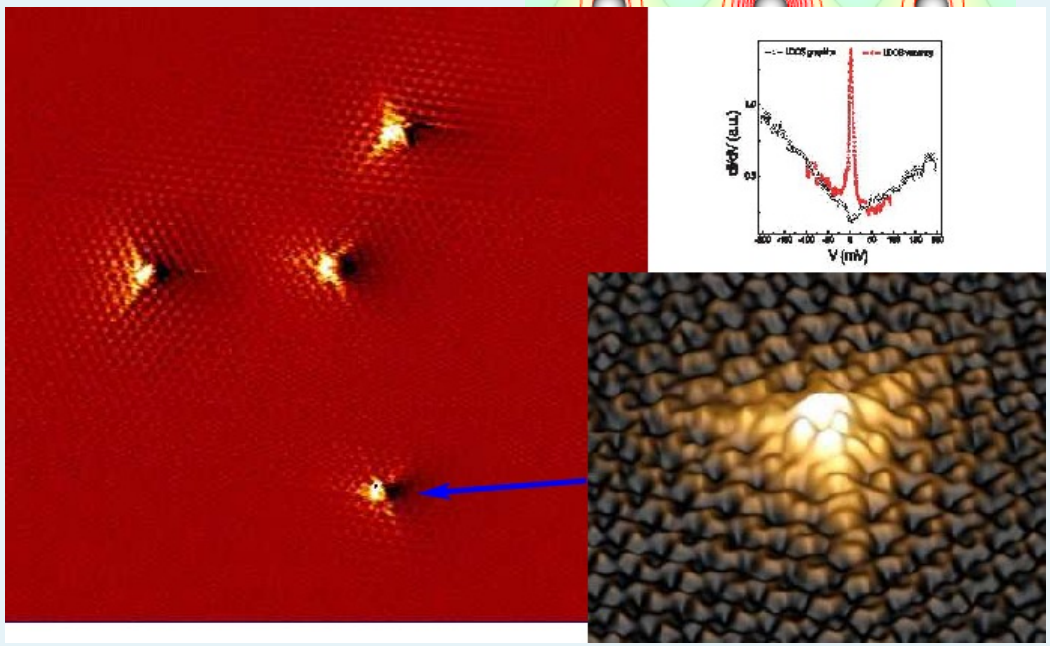
covalent



Atomic-scale defects







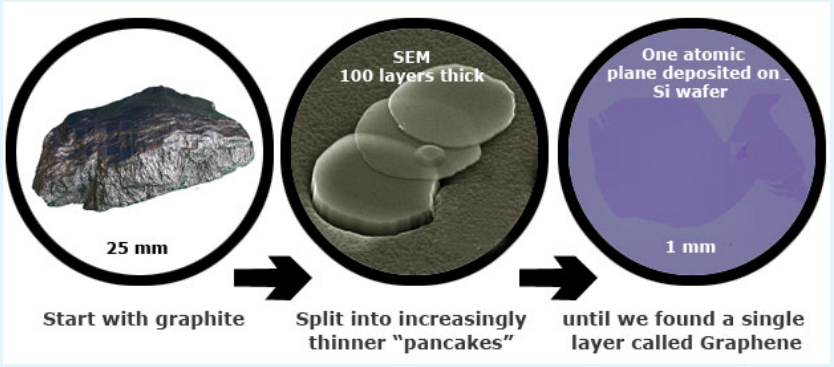
Defect induced levels at the **Fermi level** affect **chemical and transport** properties

Production

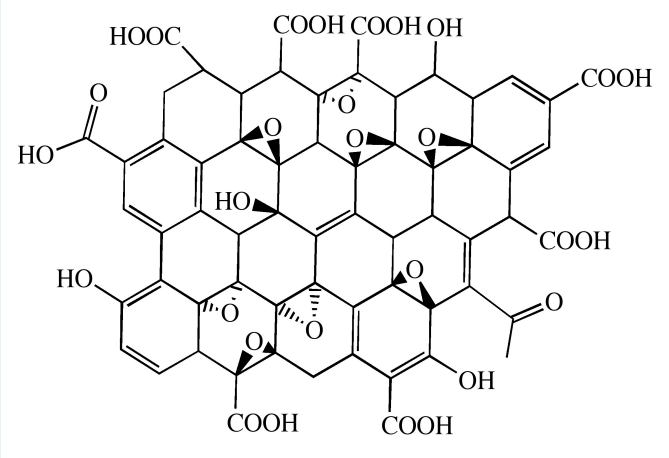
- Exfoliation
- Graphene oxide reduction
- Si sublimation in SiC
- Chemical vapor decomposition on metals not forming carbides

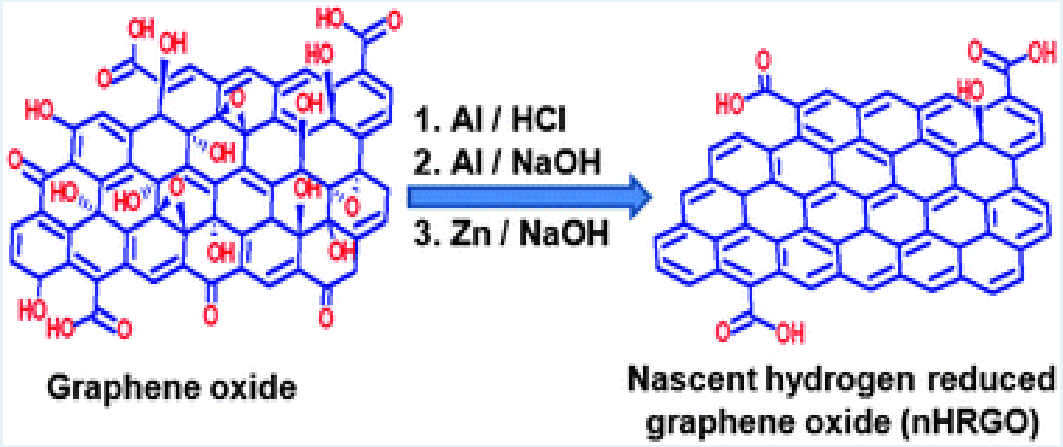
Production


Scotch tape method of making
graphene
from HOPG

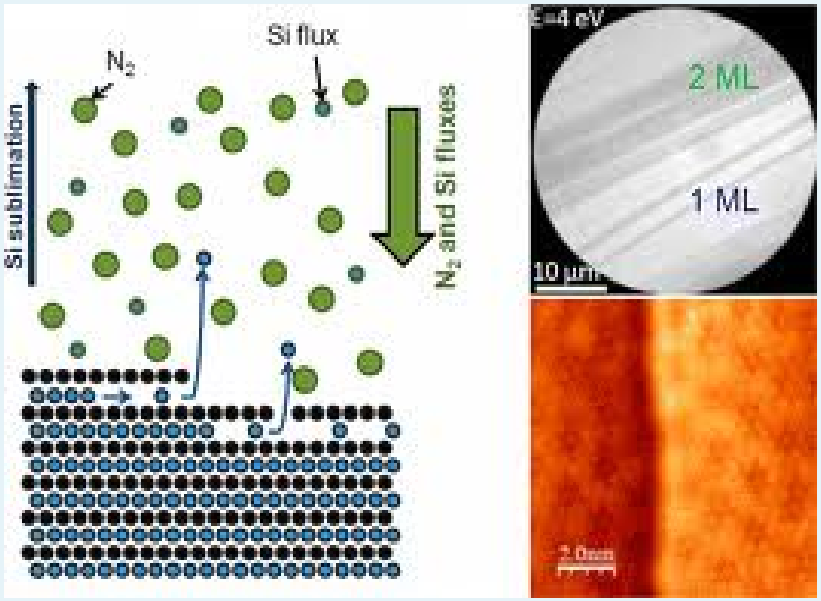

SEM
100 layers thick
One atomic
plane deposited on
Si wafer
25 mm
1 mm
Start with graphite
Split into increasingly
thinner "pancakes"
until we found a single
layer called Graphene

Production

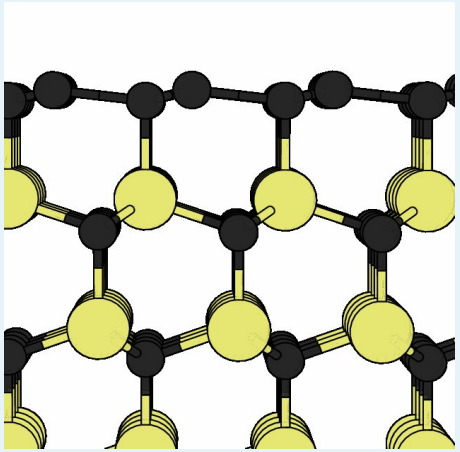

HOOC
COOH COOH OH
COOH
HO
O
HO
COOH
HO
O
O
O
OH
COOH
COOH

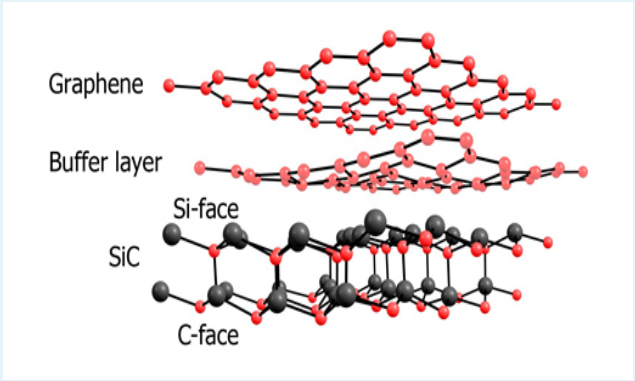

1. Al / HCl
2. Al / NaOH
3. Zn / NaOH
Graphene oxide
Nascent hydrogen reduced graphene oxide (nHRGO)

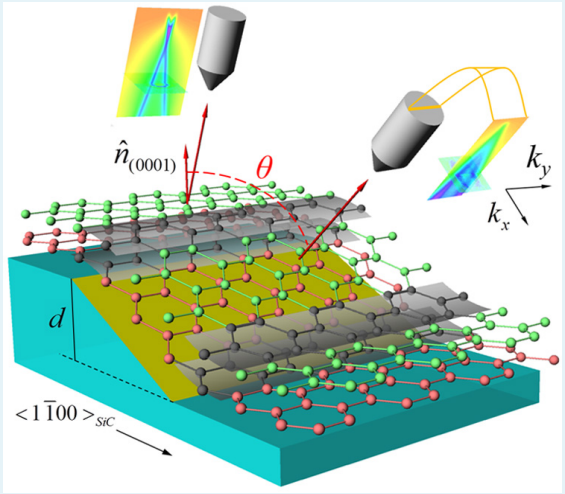
Production


Si flux
N_2
Si sublimation
N_2 and Si fluxes

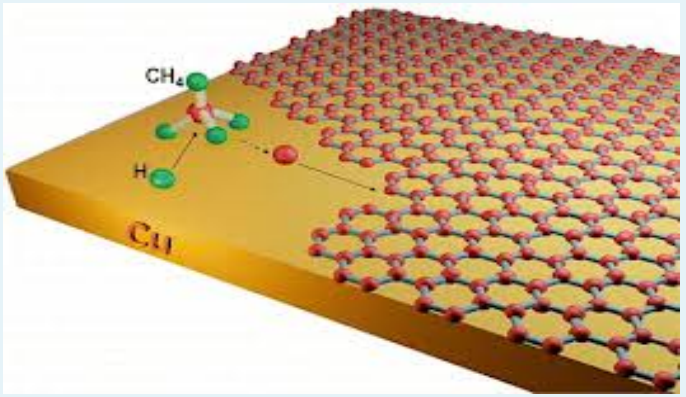
E=4 eV
2 ML
1 ML
10 μm
2.0nm

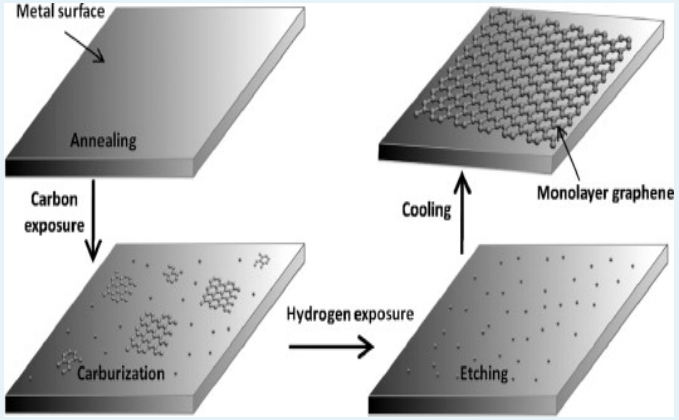


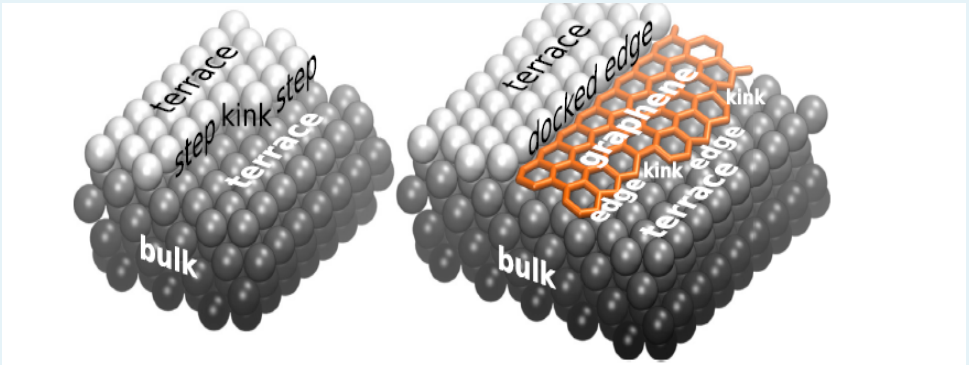

Graphene
Buffer layer
Si-face
SiC
C-face

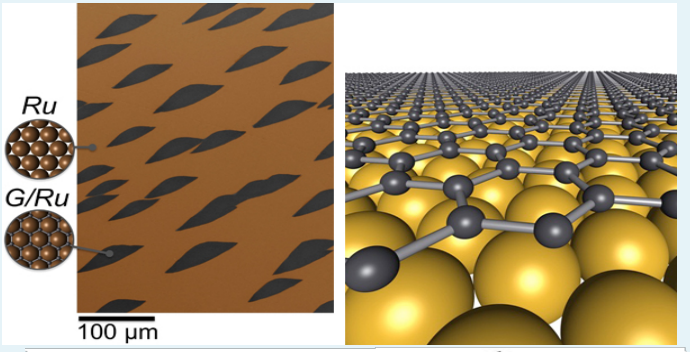

$\hat{n}_{(0001)}$
θ
k_y
k_x
d
$<1\bar{1}00>_{SiC}$

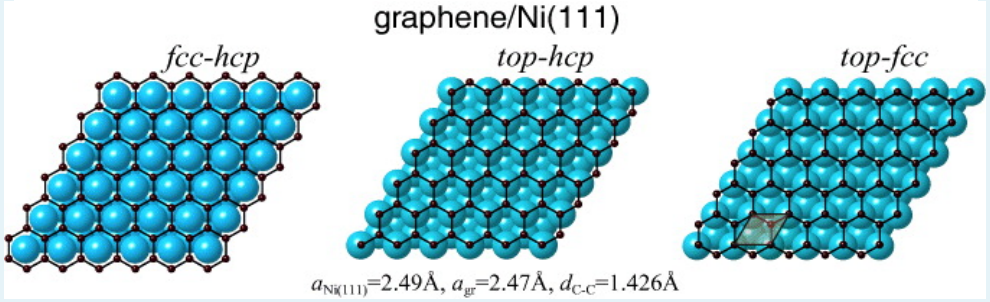
Production

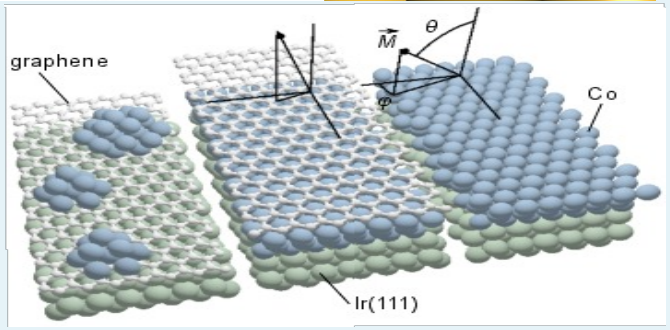

CH4
H
Cu


Metal surface
Annealing
Carbon exposure
Carburization
Hydrogen exposure
Etching
Cooling
Monolayer graphene

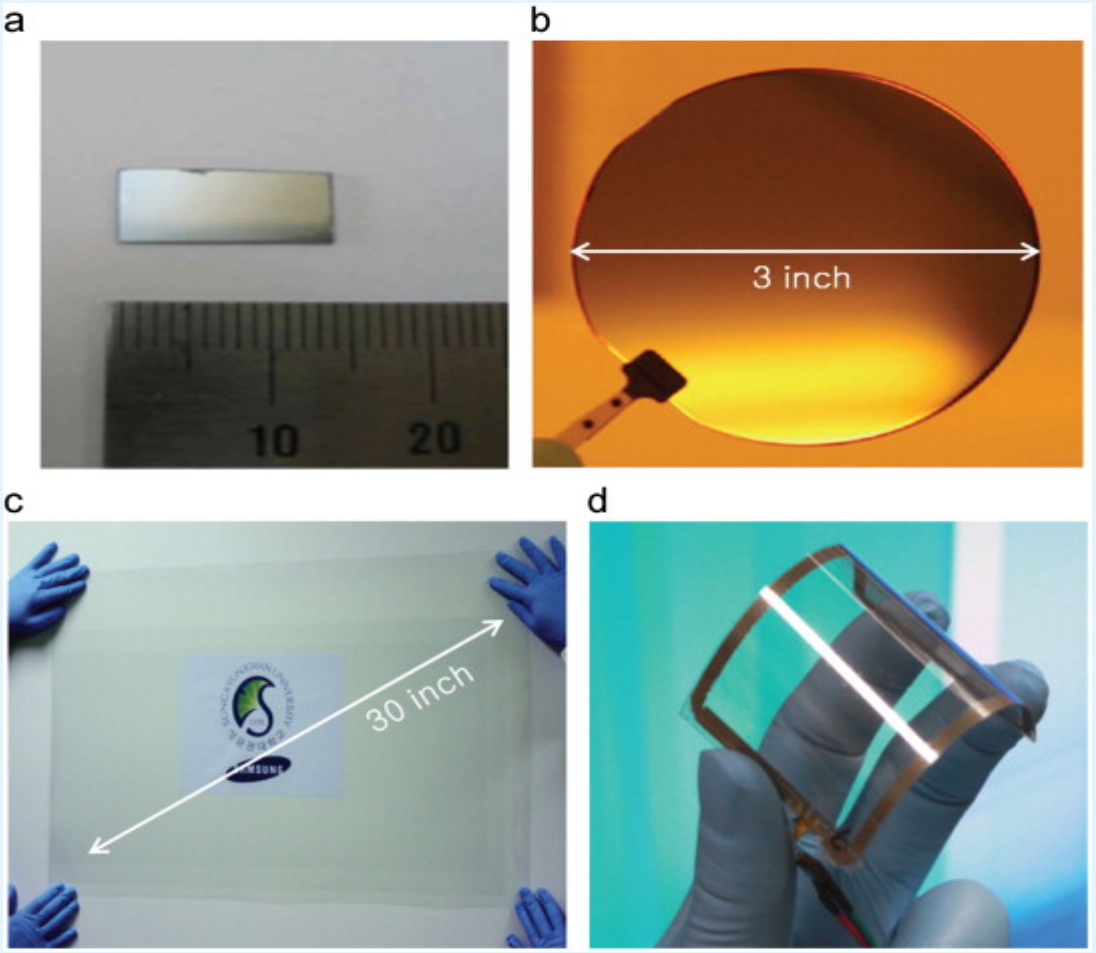

terrace
step
kink
step
terrace
bulk
terrace
docked edge
graphene
kink
edge
kink
edge
terrace
bulk


Ru
G/Ru
100 μm

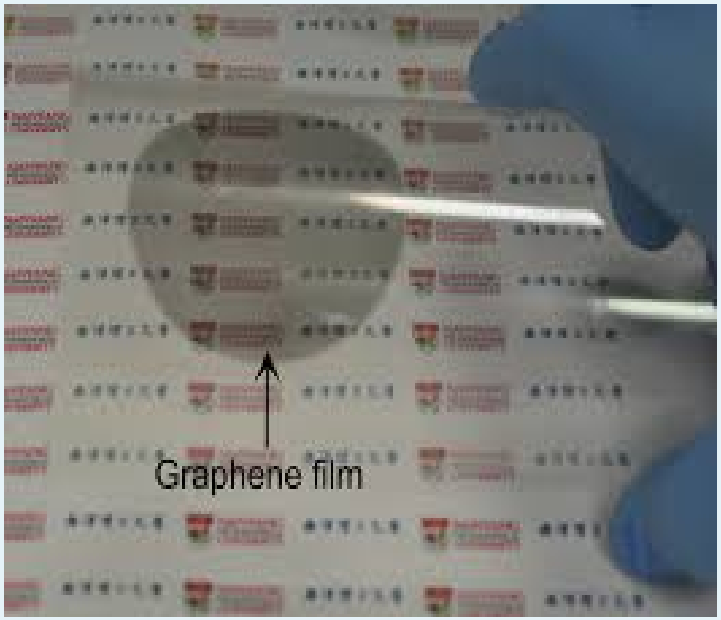

graphene/Ni(111)
fcc-hcp
top-hcp
top-fcc
$a_{Ni(111)}$=2.49Å, a_{gr}=2.47Å, d_{C-C}=1.426Å

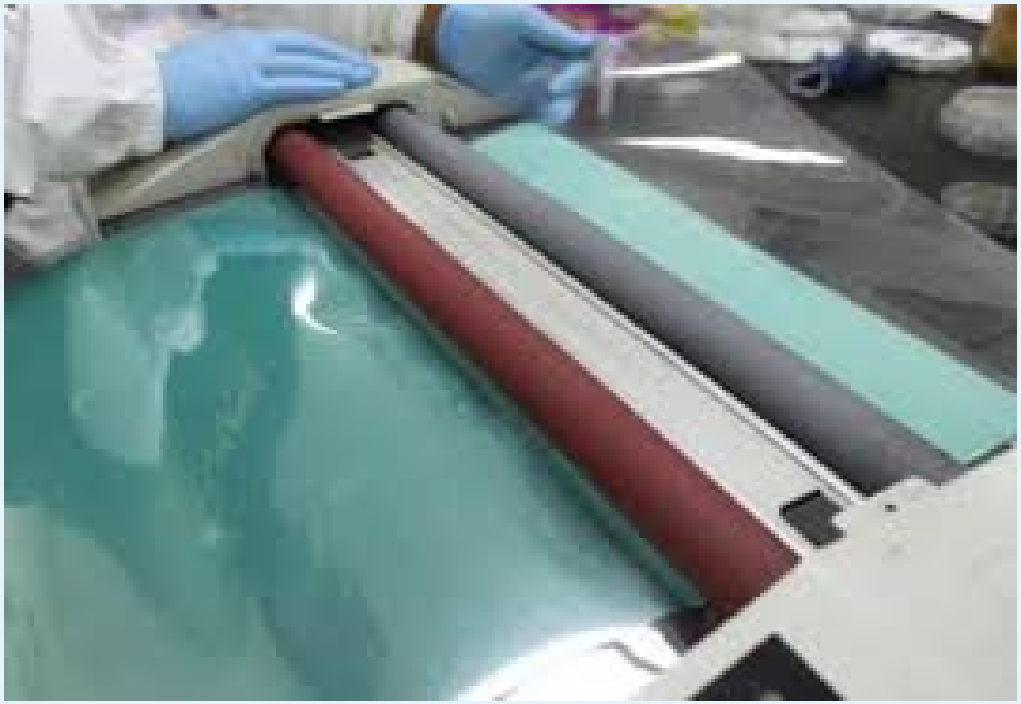

graphene
Co
Ir(111)

Production

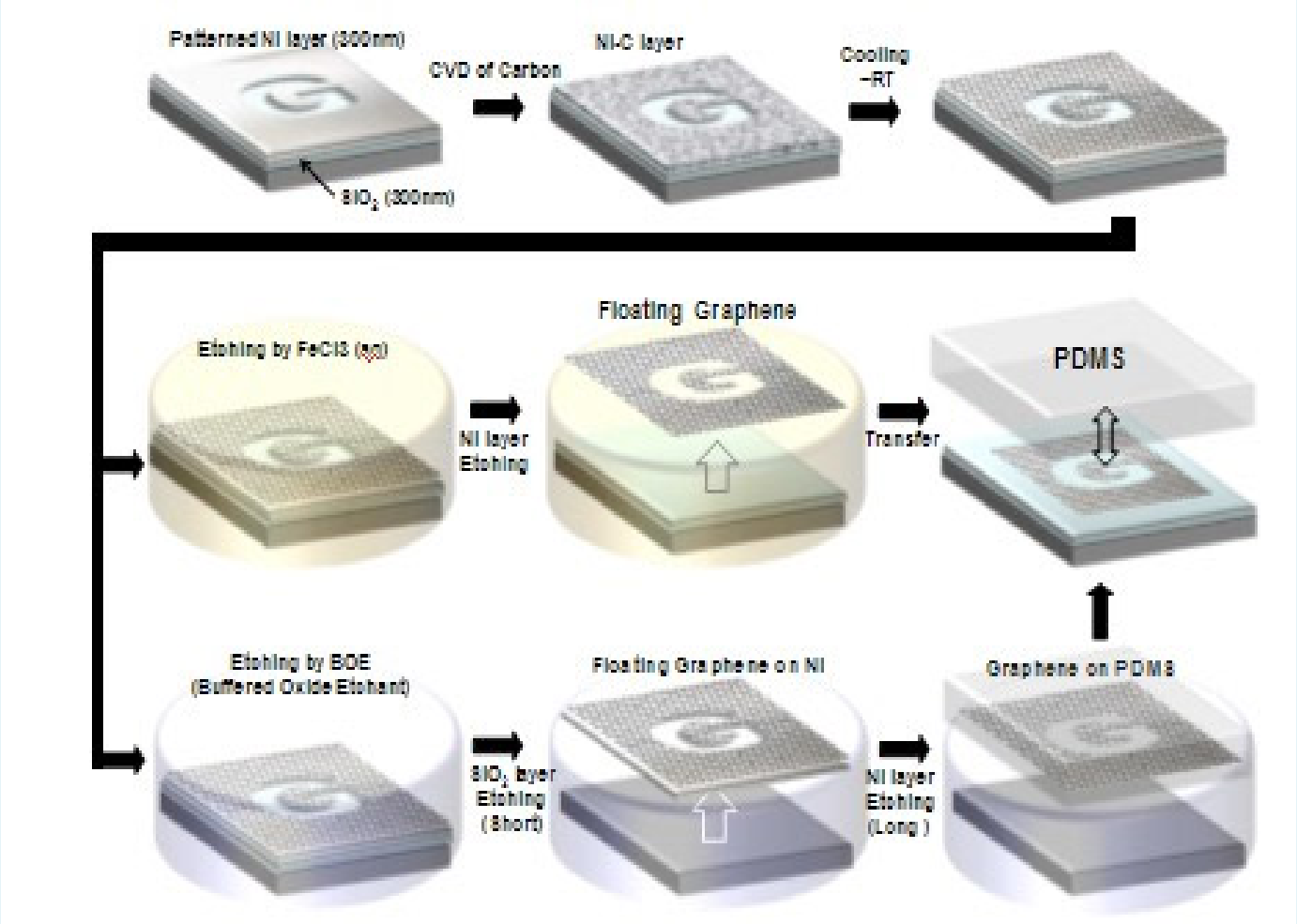


Production

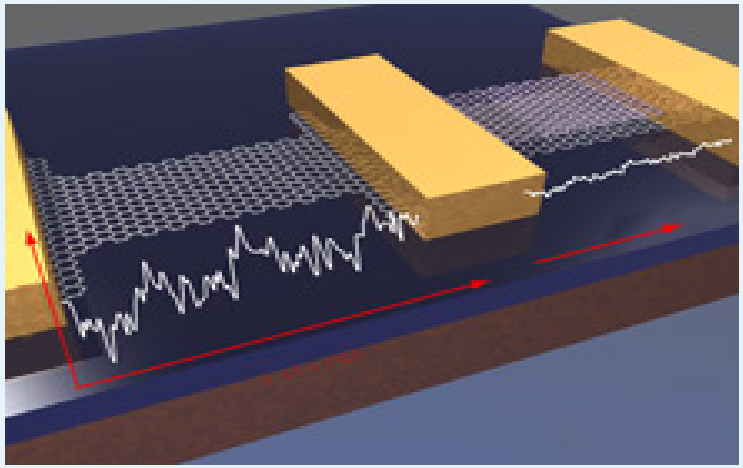


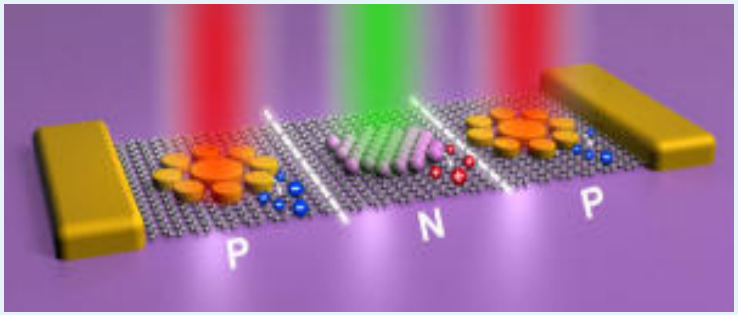


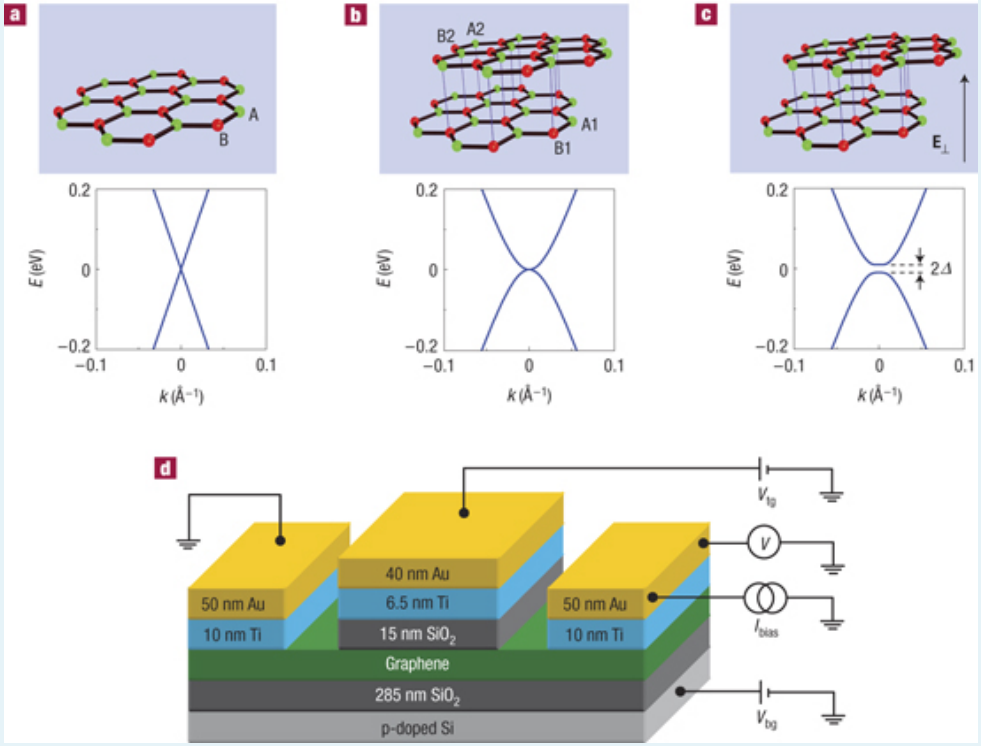
Devices


Patterned Ni layer (300nm)
CVD of Carbon
Ni-C layer
Cooling
~RT
SiO_2 (300nm)
Floating Graphene
Etching by FeCl3 (aq)
Ni layer
Etching
Transfer
PDMS
Etching by BOE
(Buffered Oxide Etchant)
Floating Graphene on Ni
Graphene on PDMS
SiO_2 layer
Etching
(Short)
Ni layer
Etching
(Long)

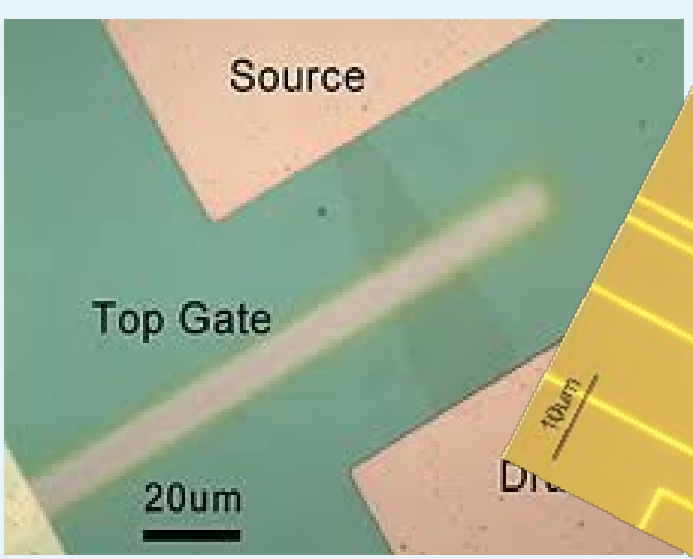
Devices

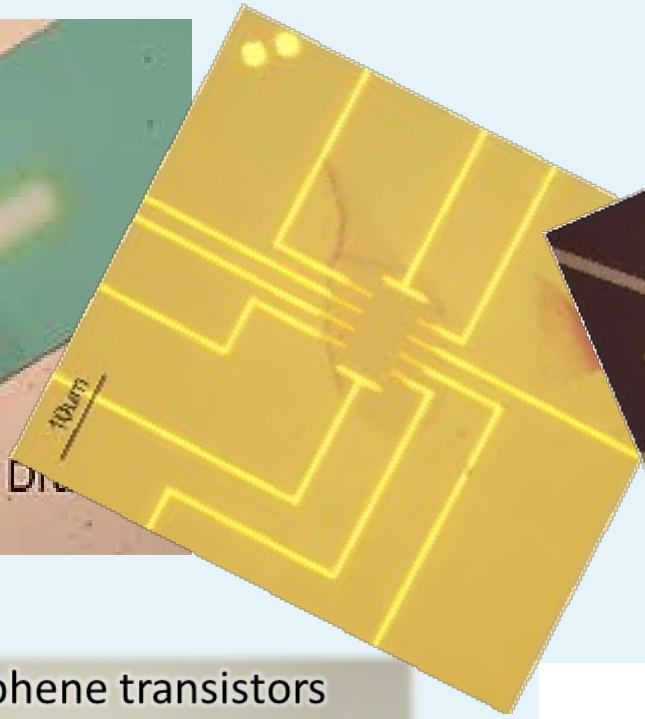


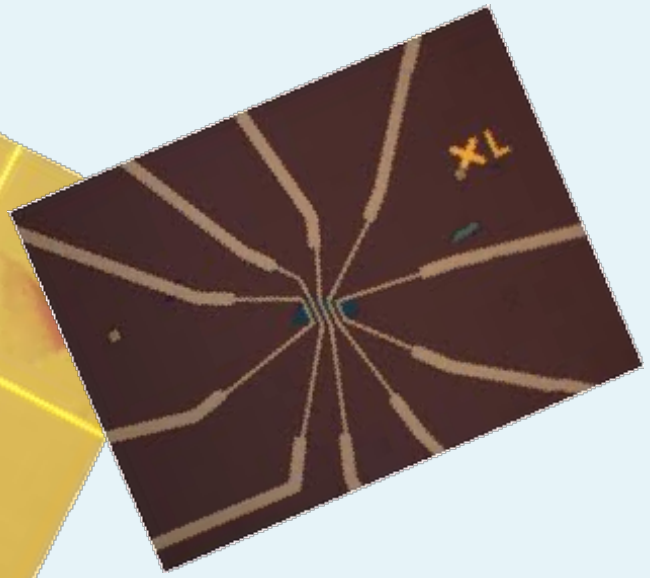

P
N
P

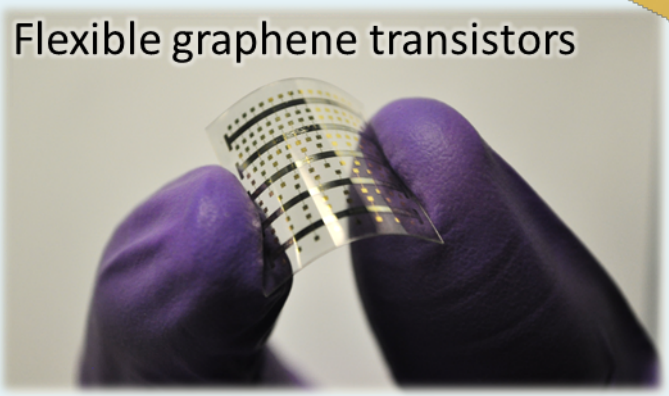

a
A
B
b
B2
A2
A1
B1
c
E⊥
0.2
0
−0.2
E (eV)
−0.1
0
0.1
k (Å⁻¹)
2Δ
d
50 nm Au
10 nm Ti
40 nm Au
6.5 nm Ti
15 nm SiO2
Graphene
285 nm SiO2
p-doped Si
50 nm Au
10 nm Ti
Vtg
V
Ibias
Vbg

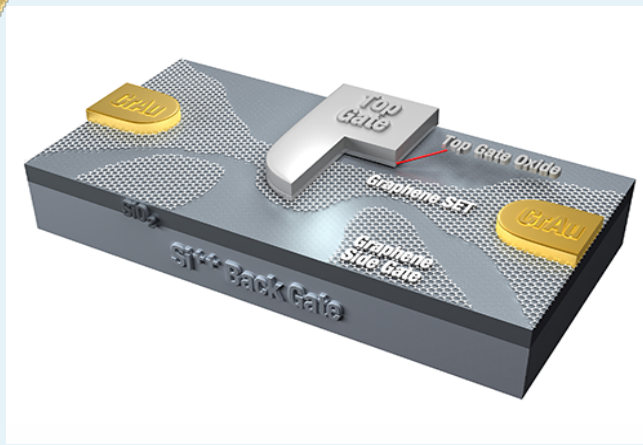
Devices


Source
Top Gate
20um

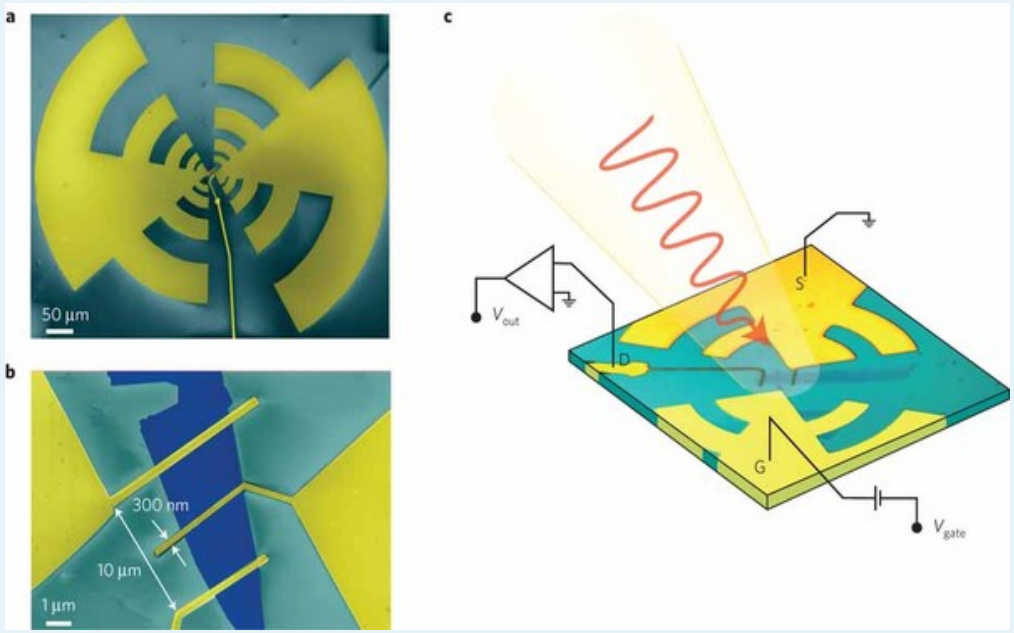

10um

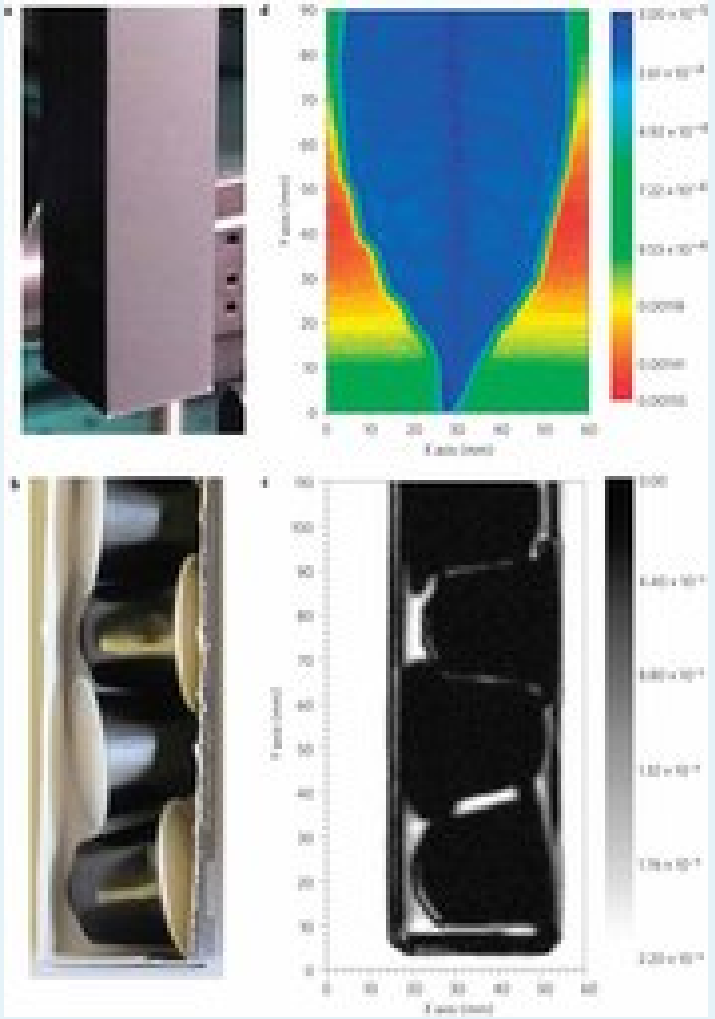

XL


Flexible graphene transistors

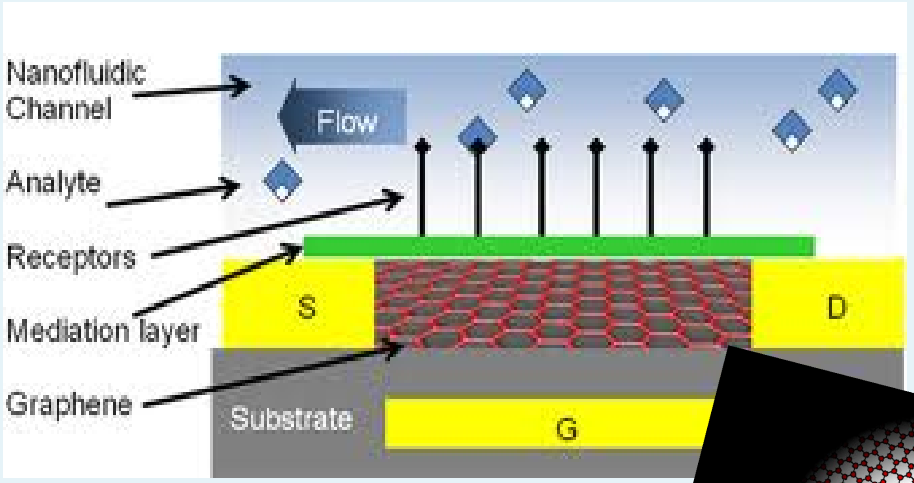

Top Gate
Top Gate Oxide
Graphene SET
Graphene Side Gate
Si++ Back Gate

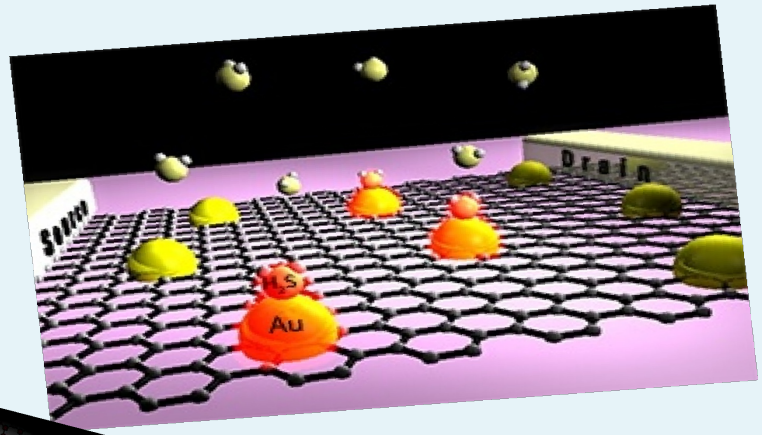
Devices

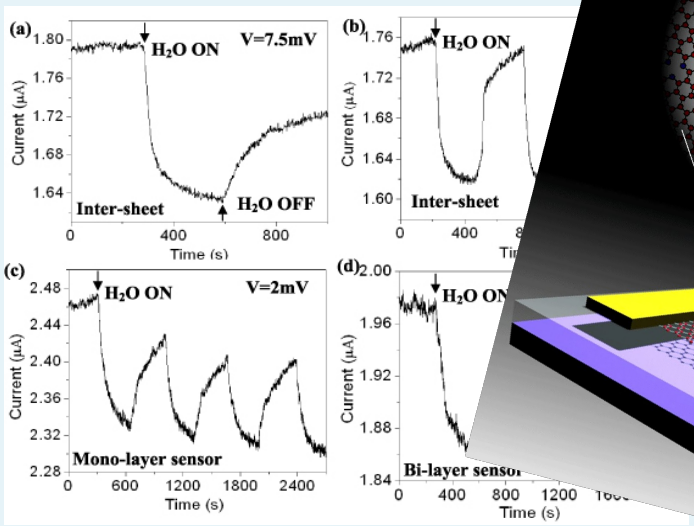


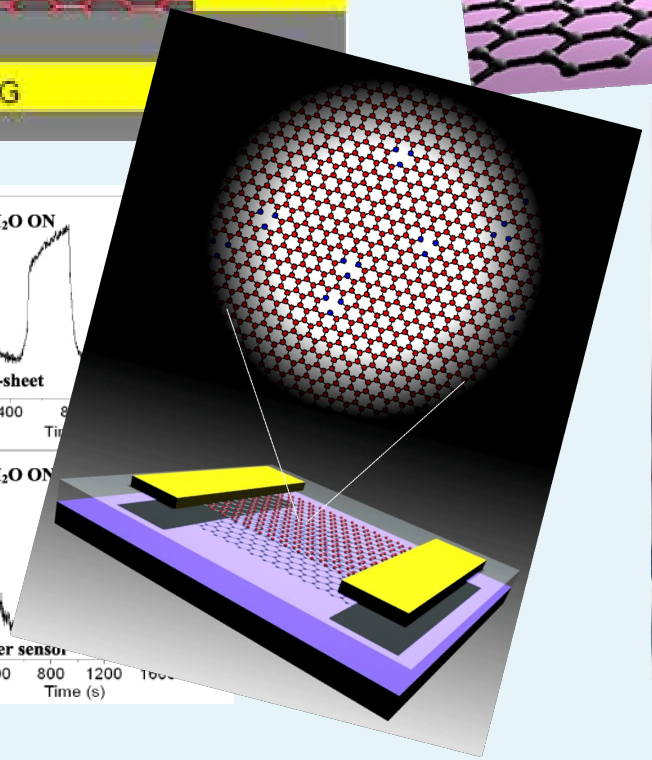


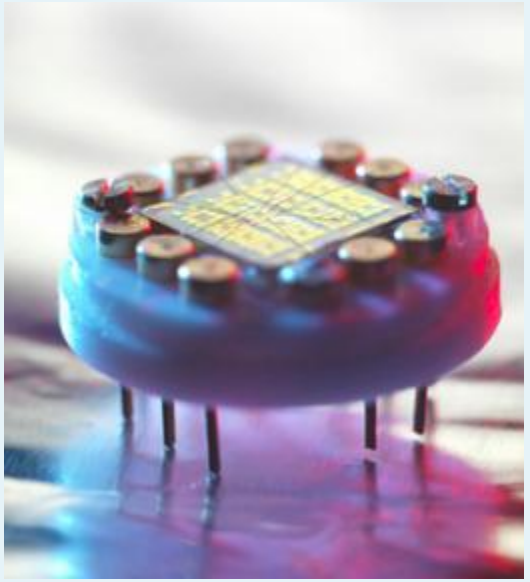
Devices


Nanofluidic Channel
Flow
Analyte
Receptors
Mediation layer
Graphene
S
D
Substrate
G

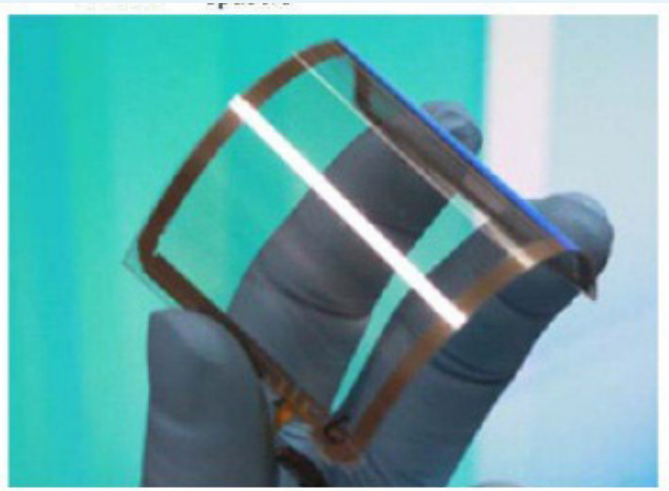

Source
Drain
H2S
Au


(a)
H2O ON
V=7.5mV
Inter-sheet
H2O OFF
Current (μA)
Time (s)
(b)
H2O ON
Inter-sheet
(c)
H2O ON
V=2mV
Mono-layer sensor
(d)
H2O ON
Bi-layer sensor

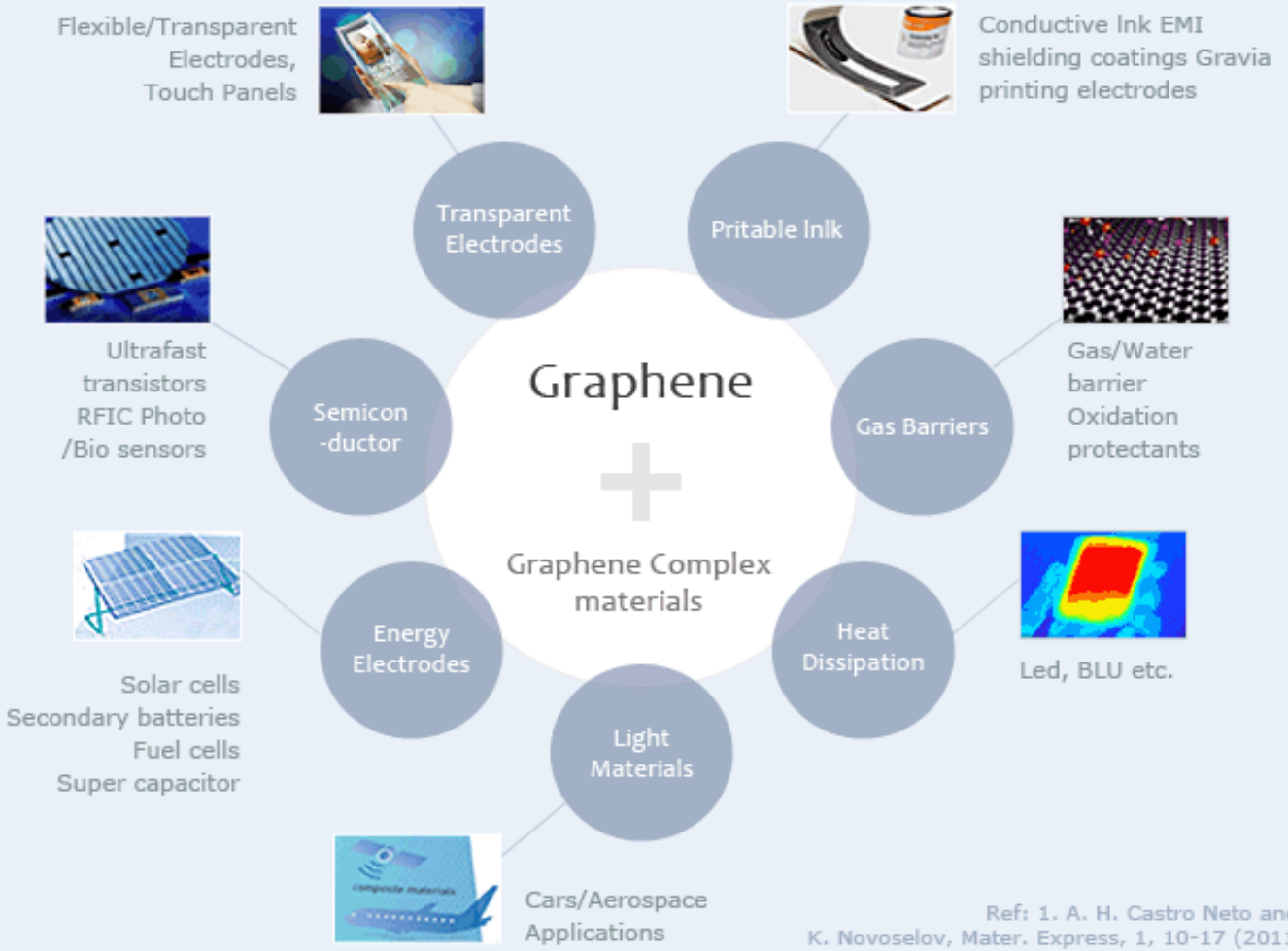




Devices



Devices


Flexible/Transparent Electrodes, Touch Panels
Transparent Electrodes
Conductive Ink EMI shielding coatings Gravia printing electrodes
Pritable Inlk
Ultrafast transistors RFIC Photo /Bio sensors
Semicon -ductor
Graphene
+
Graphene Complex materials
Gas Barriers
Gas/Water barrier Oxidation protectants
Solar cells Secondary batteries Fuel cells Super capacitor
Energy Electrodes
Heat Dissipation
Led, BLU etc.
Light Materials
Cars/Aerospace Applications
Ref: 1. A. H. Castro Neto and K. Novoselov, Mater. Express, 1, 10-17 (2011)