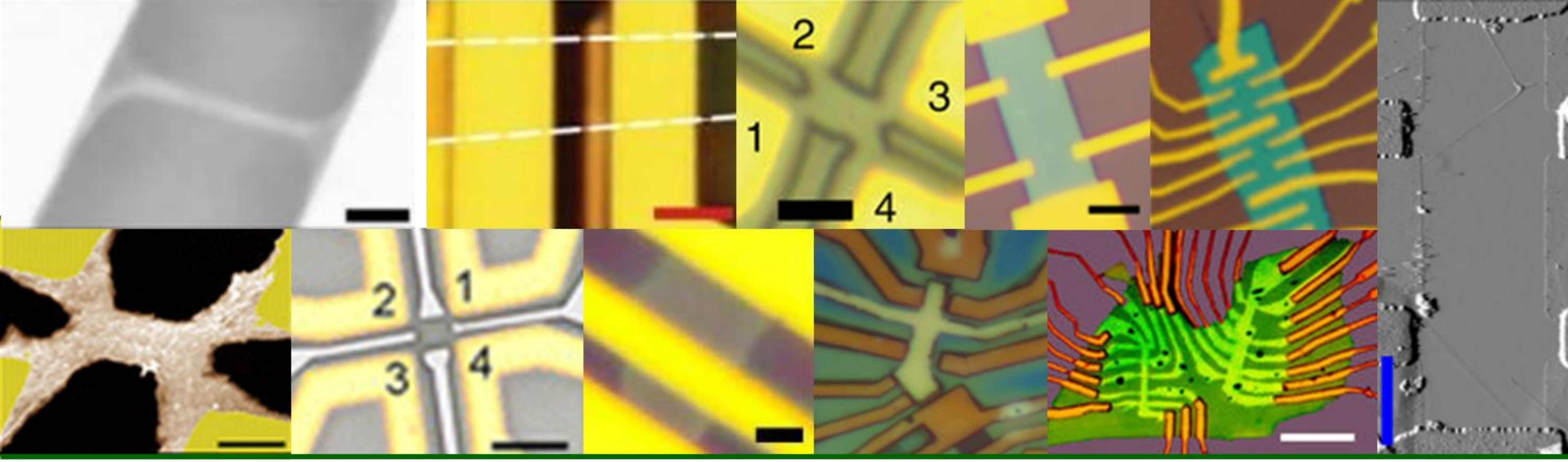



# *Studying quantum physics in atomically thin van der Waals crystals*


***Dong-Keun Ki***

Department of Physics
The University of Hong Kong

# *Low-temperature mesoscopic quantum physics*

| Length | | Temperature | |
|---|---|---|---|
| m | $10^0$ m | | $10^6$ K |
| mm | $10^{-3}$ m | | $10^3$ K |
| μm | $10^{-6}$ m | | 100 K |
| nm | $10^{-9}$ m | mK | $10^{-3}$ K |
| Å | $10^{-10}$ m | μK | $10^{-6}$ K |

*Image from NASA*

*Classical physics*
*($F = ma$)*

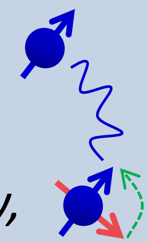
*High-energy physics*
- *LHC ($10^{12}$ K)*
- *Supernova (~$10^5$ K)*
- *Sun (5777 K)*

**Direct study**

**Transport of many quantum particles ($10^{16\text{-}24}$ cm$^{-3}$) in a mesoscopic scale**

- ***Nano-electronic device fabrication***

*Quantum-to-Classical physics*
*Quantum coherence & correlations,*
*Fluctuations, Band-structure topology,*
*…*



- ***Cryogenics***
- ***Low-noise measurement***

**Final project**

**Final project**

*Quantum physics*
*($H\psi = E\psi$)*

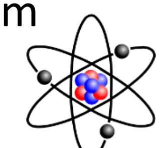


*Image from Google*

*Ultra cold atoms: dilute (~$10^{14}$ cm$^{-3}$)*

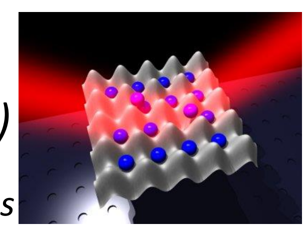


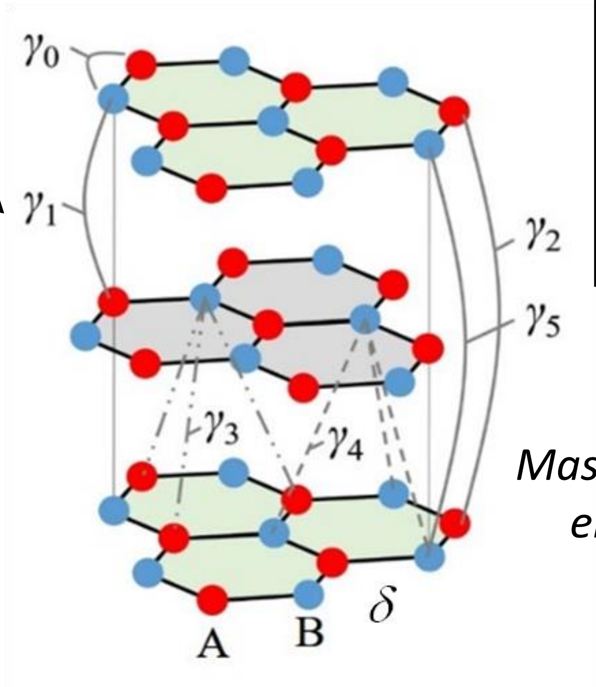
*Image from Lens*

# *van der Waals coupled layered materials → defect-free monolayers*

*In graphite, each graphene layers are coupled by a van der Waals (vdW) force which is much weaker than chemical bonds.*

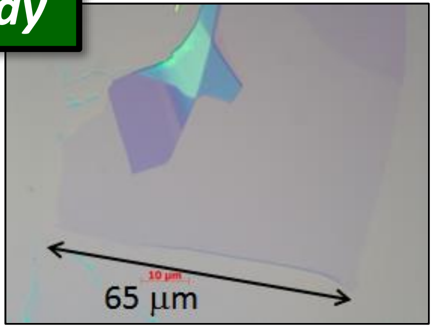
*Thus, it can be exfoliated to produce "defect-free" atomically thin layers*

*van der Waals interaction*

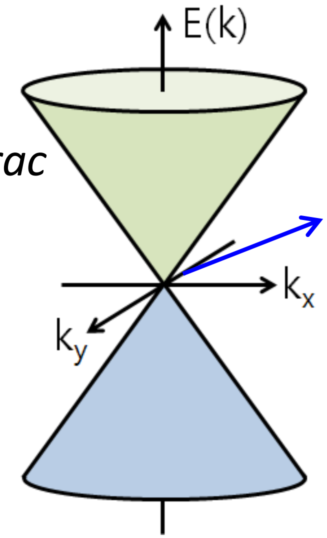



*Graphite* → *Mechanical, Chemical* → *Graphene*

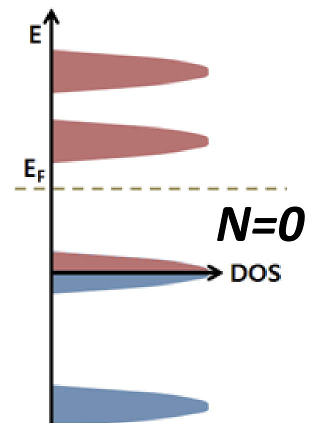
***Direct study***




*Massless Dirac electrons*




*Charge neutrality point (CNP)*

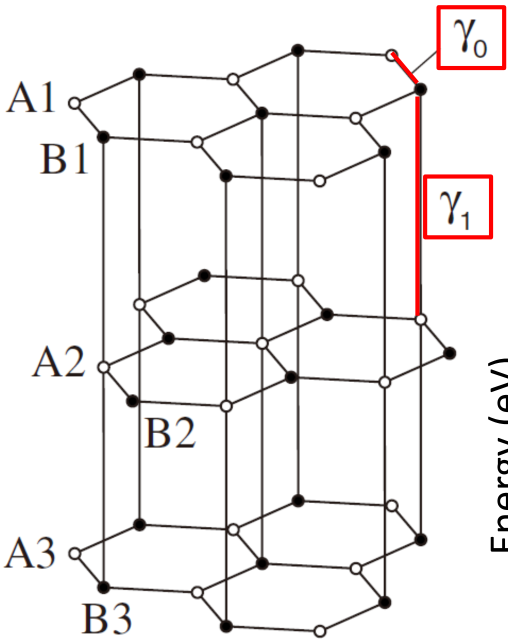



*Characteristic N=0 Landau level*

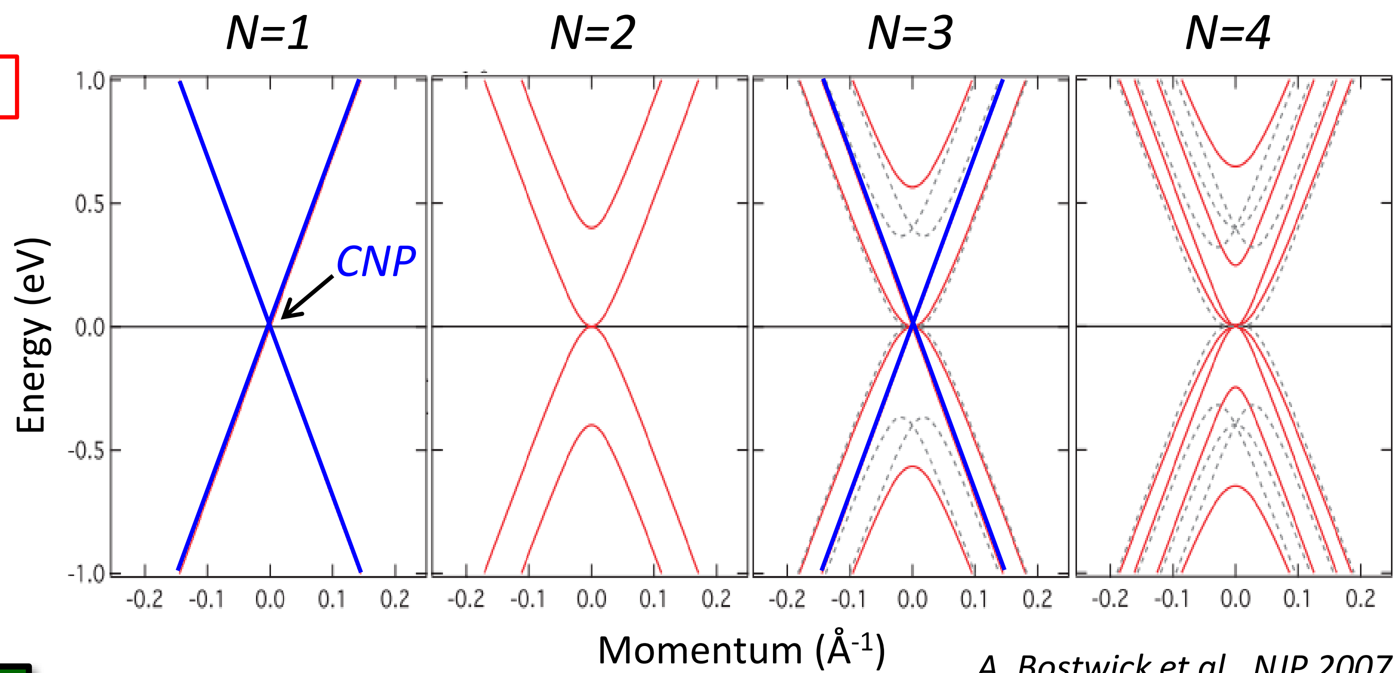
# N-layer graphene: a family of closely related electronic systems

*Consider two nearest neighbor hopping parameters: $\gamma_0$ and $\gamma_1$*

*Bernal-stacking*




- *N=odd: **1 monolayer-like**, (N-1)/2 bilayer-like bands*
- *N=even: N/2 bilayer-like bands*




*A. Bostwick et al., NJP 2007*

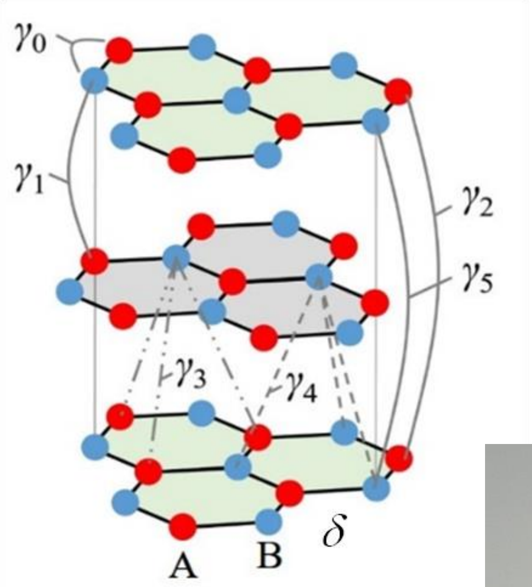
***Final project***

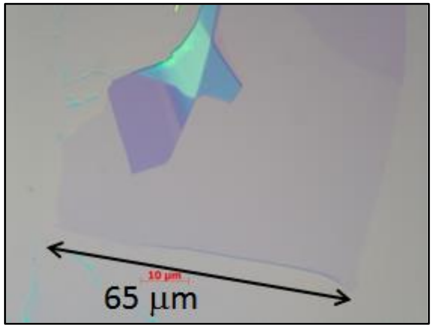
*Electronic properties vary with atomic structures.*
*Different from conventional 2D electron gas systems.*

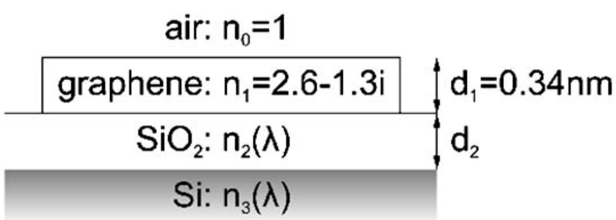
# Searching for N atomically thin layers

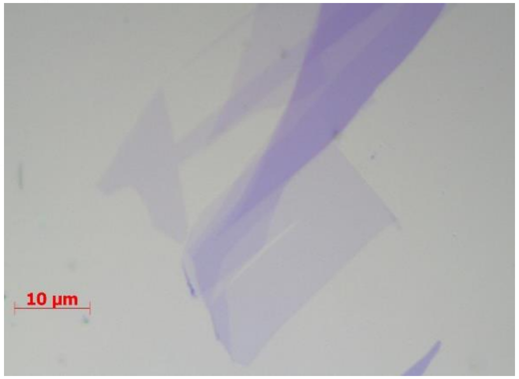
*van der Waals interaction*

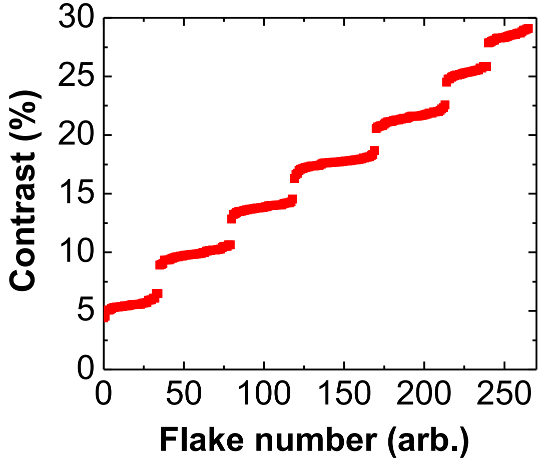
*Graphite* → *Mechanical, Chemical* → *Graphene*



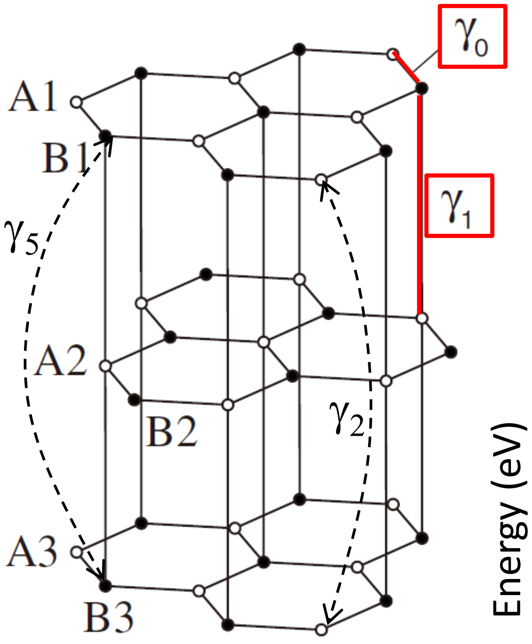




*Calculate* → *Exfoliate* → *Observe* → *Analyze*

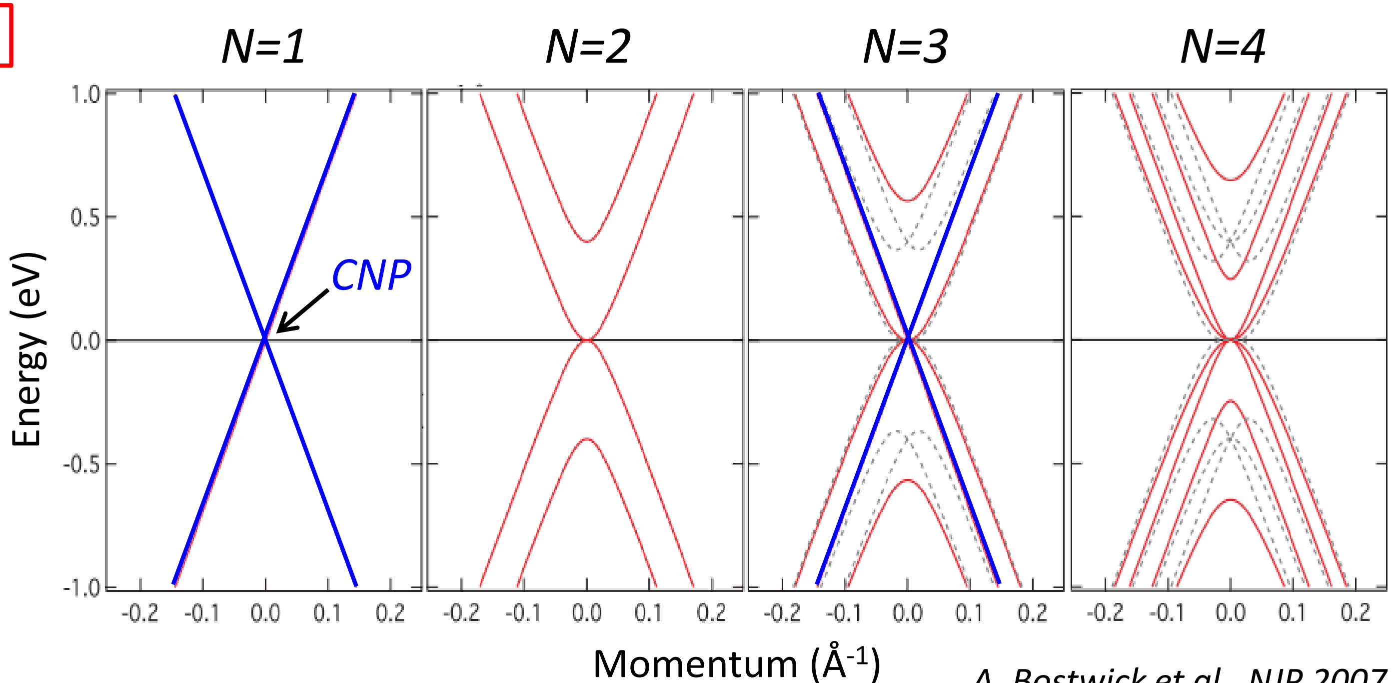
# *Electric and Thermoelectric Properties for N=1,2,3*

*Bernal-stacking*

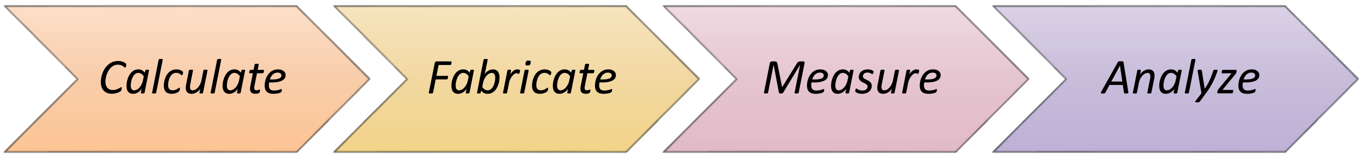



*Consider two nearest neighbor hopping parameters: $\gamma_0$ and $\gamma_1$*

- *N=odd: **1 monolayer-like**, (N-1)/2 bilayer-like bands*
- *N=even: N/2 bilayer-like bands*




*A. Bostwick et al., NJP 2007*



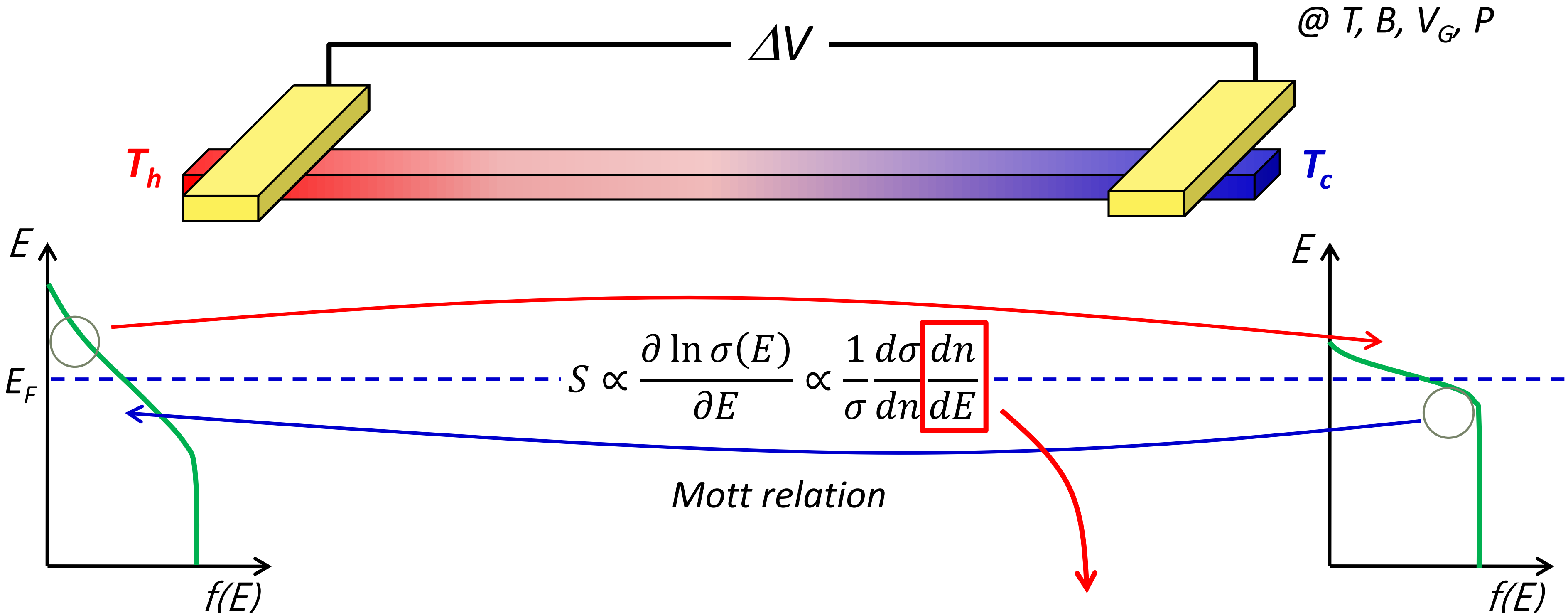
# Electric and Thermoelectric Properties for N=1,2,3

*Electric quantities :*
*electric currents or voltages*

*Thermodynamic quantities :*
*temperature or entropy*

→ **Thermoelectric effect**

$S = -\Delta V/\Delta T \quad (\Delta T = T_h - T_C)$



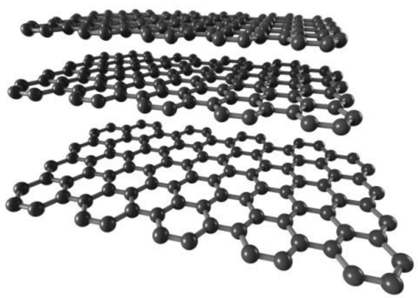

$$S \propto \frac{\partial \ln \sigma(E)}{\partial E} \propto \frac{1}{\sigma}\frac{d\sigma}{dn}\frac{dn}{dE}$$

*Mott relation*

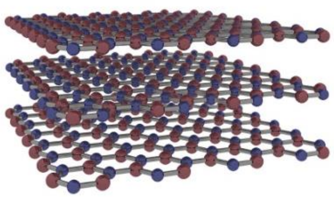
*S depends sensitively on how E changes with electron density (n)*

# 2D family: layered materials that can be tinned down to atomic-layers

**Graphene family (hexagonal layers)**



Graphene layers

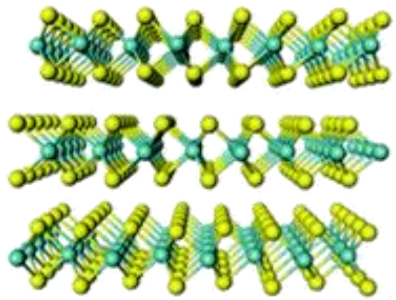


hBN layers

**Buckled graphene**

Back phosphorus

**2D chalcogenides ($MX$, $MX_2$, $M_2X_3$, etc)**



2D dichalcogenides ($MX_2$)

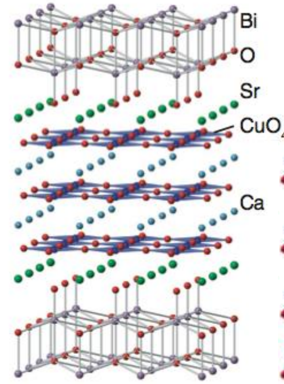
- Semiconducting
- Semimetallic
- Superconducting

MX: layered semiconductors (GaSe, GaTe, InSe, …)

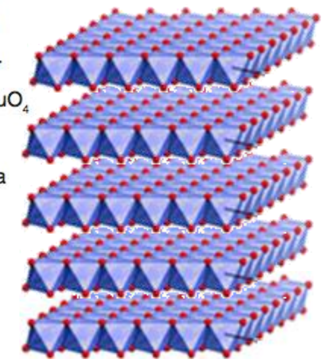
$Bi_2Se_3$: topological insulator

and others….

**2D oxides**




Bi-2212



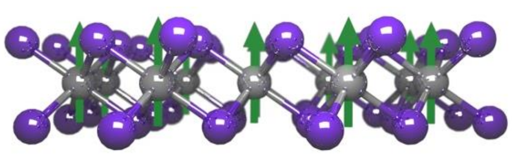
$MnO_2$

**Magnetic materials**

$CrI_3$ ; 2H-$VSe_2$

$Cr_{1/3}NbS_2$

etc



# True 2D nature promotes *interactions with environment*

**Charge transport occurs at the surface**

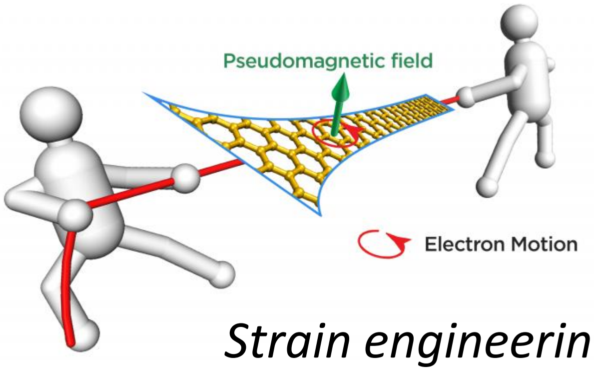
*Large experimental accessibility*

- *Electrostatic gating*
- *Scanning probes*
- *Optical investigations, …*

*Easy contact engineering*

- *Superconducting contacts*
- *Magnetic contacts*
- *Other 2D crystals*

*Atomically thin = Flexible*




*Strain engineering*
*Folding—Unfolding*

*Chemical or surface engineering*

**Final project**

**Direct study**

*Exfoliate* → *Search* → *Fabricate* → *Measure* → *Analyze*