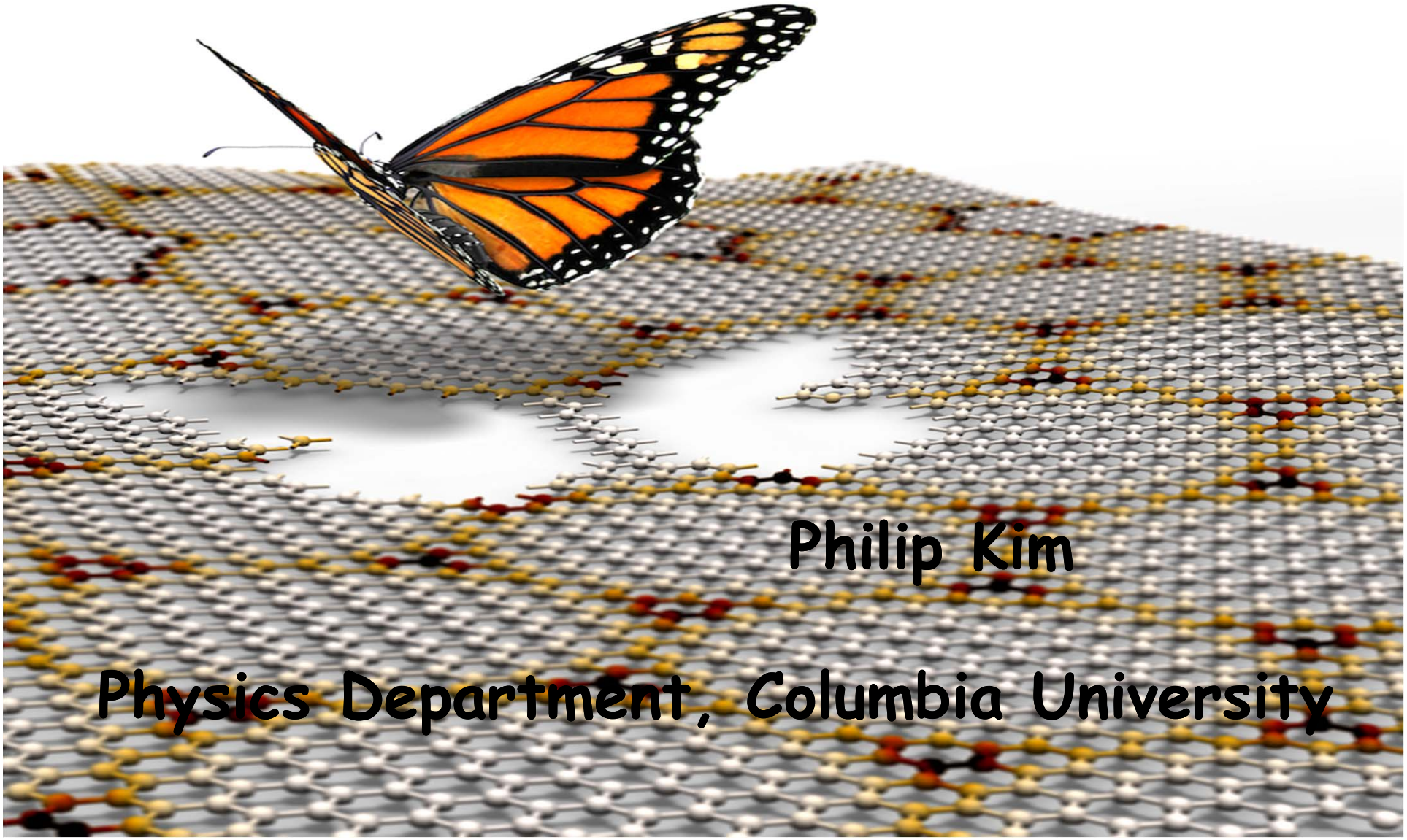
Materials in 2-dimension and beyond

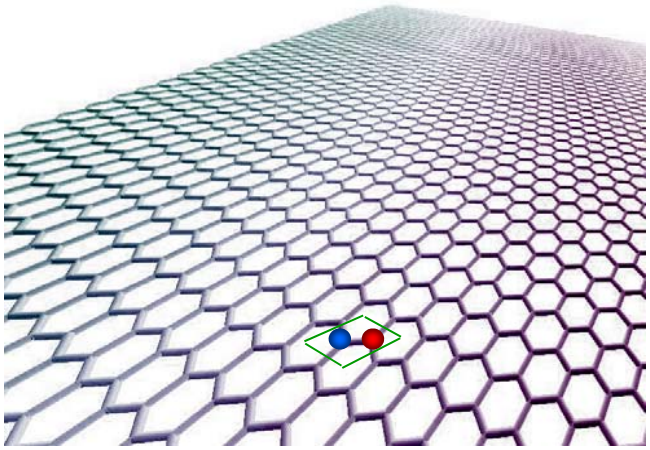


Philip Kim

Physics Department, Columbia University

Graphene: Exotic Electronic Properties

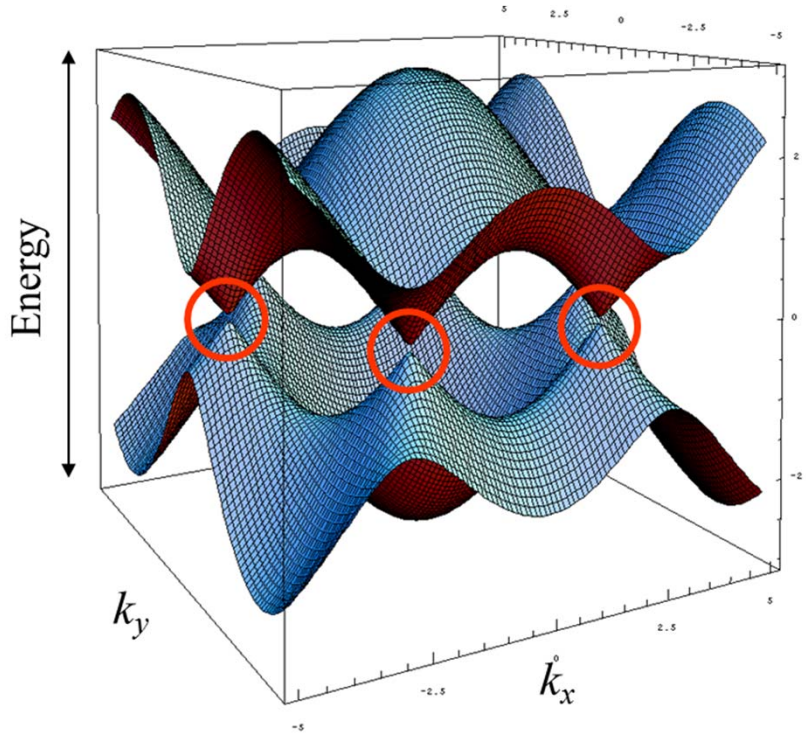
Graphene in real space



Pseudo Spin

$$H_{eff} = \pm \hbar v_F \vec{\sigma} \cdot \vec{k}'_{\perp}$$

Graphene band structure



- **Linear dispersion: zero effective mass**
- **Chiral nature of electron: pseudo spin symmetry**

Quantum Hall Effect in Graphene (2005)

Vol 438|10 November 2005|doi:10.1038/nature04233 nature

LETTERS

Two-dimensional gas of massless Dirac fermions in graphene

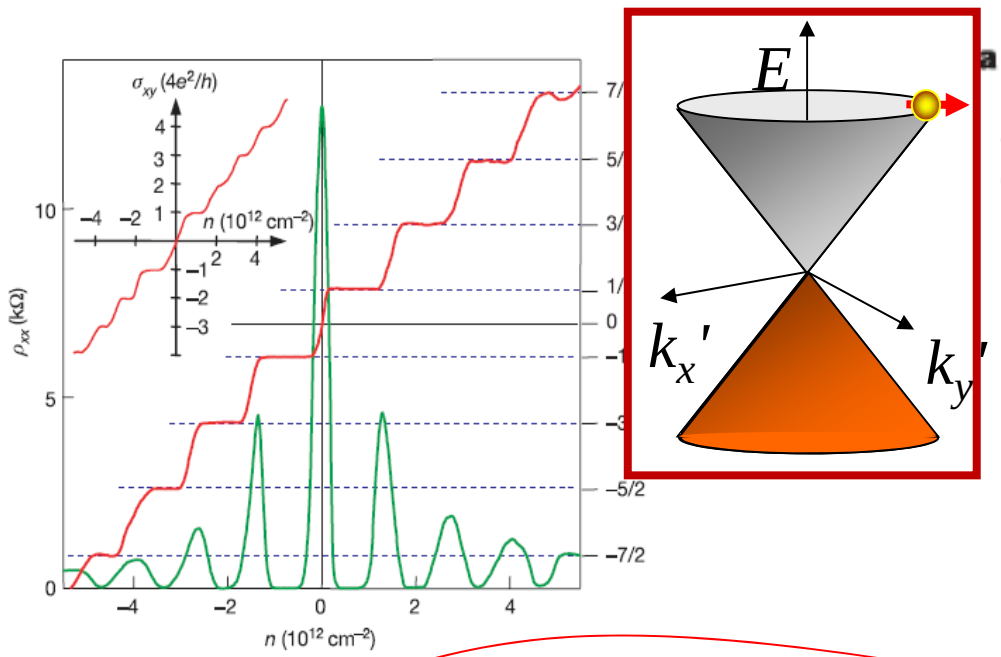
K. S. Novoselov[1], A. K. Geim[1], S. V. Morozov[2], D. Jiang[1], M. I. Katsnelson[3], I. V. Grigorieva[1], S. V. Dubonos[2] & A. A. Firsov[2]

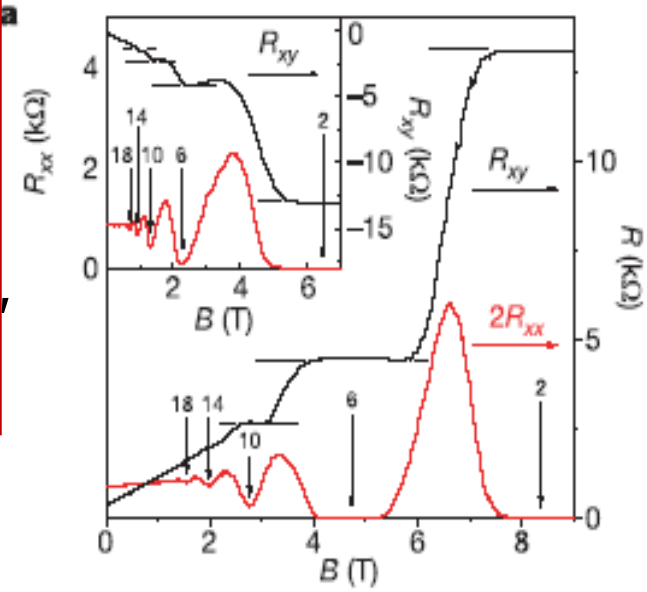
Vol 438|10 November 2005|doi:10.1038/nature04235 nature

LETTERS

Experimental observation of the quantum Hall effect and Berry's phase in graphene

Yuanbo Zhang[1], Yan-Wen Tan[1], Horst L. Stormer[1,2] & Philip Kim[1]





Quantization:

$$R_{xy}^{-1} = 4\left(n + \frac{1}{2}\right)\frac{e^2}{h}$$

spin (2) X pseudo-spin (2)

pseudo-spin rotation

Graphene Materials and Applications

Flexible/Transparent Electrodes/Touch Panels

Transparent Electrodes

Printable Inks

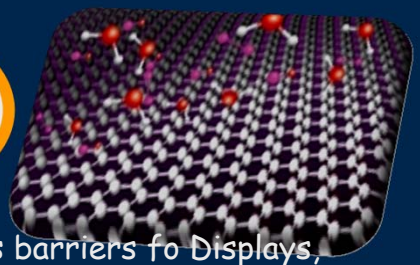
Conductive Ink, EMI shields

Semi-conductors

Large-Scale CVD Graphene + Graphene Nanoplatelet Composites

Gas Barriers

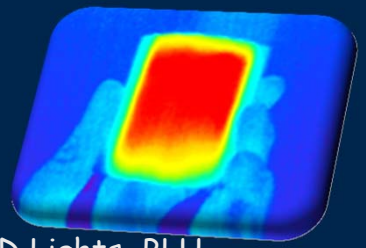
Ultrafast Transistors, RFIC, Photo/Bio/Gas Sensors



Gas barriers fo Displays, Solar Cells

Energy Electrodes

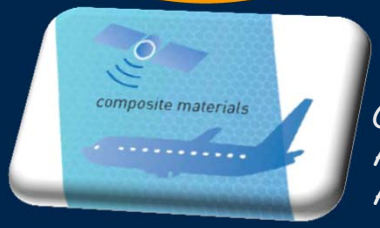
Heat Dissipation



LED Lights, BLU ECU, PC …

Composites

Super Cap./Solar Cells Secondary Batteries Fuel Cells

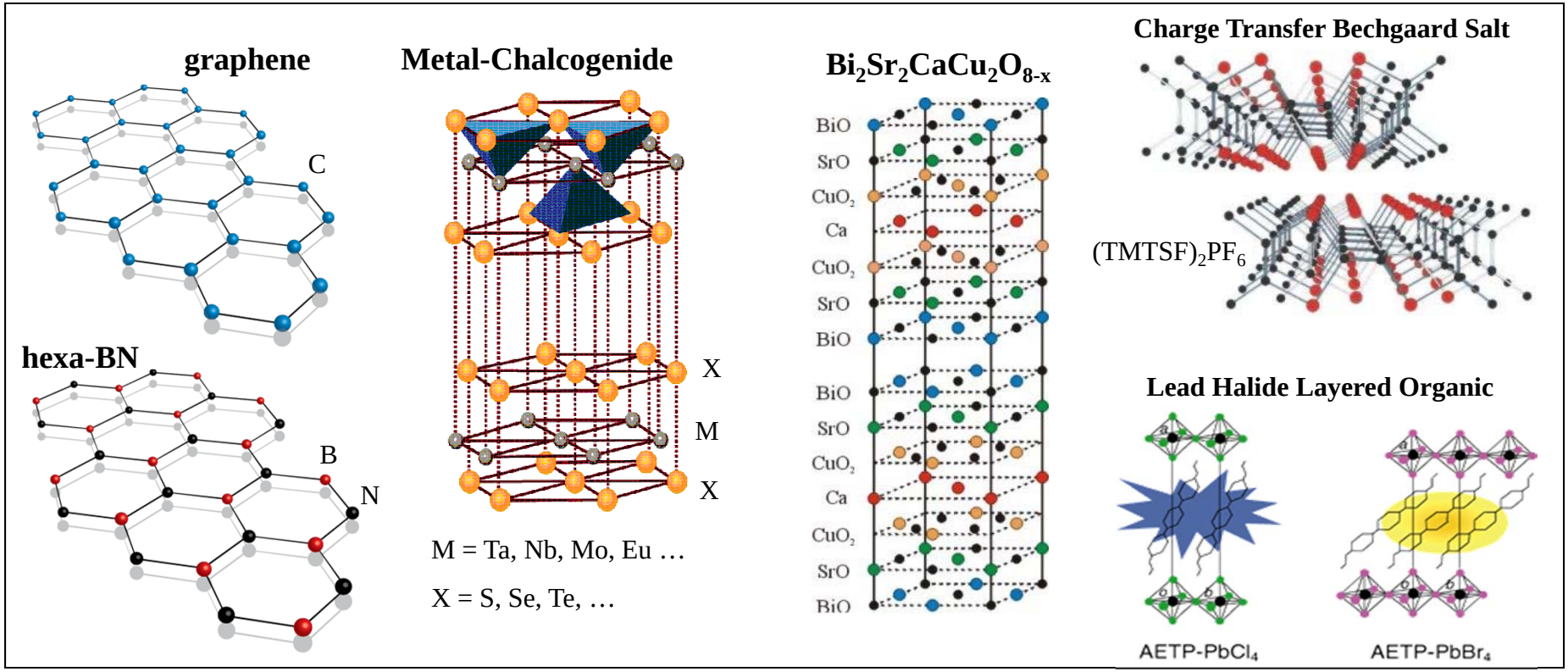


Cars, Aerospace Appliations

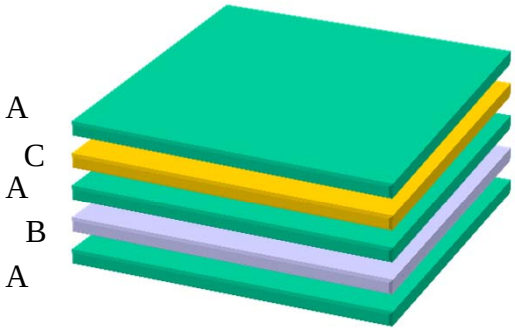
Images: Royal Swedish Academy

Courtesy: B. H. Hong

Rise of 2D van der Waals Systems

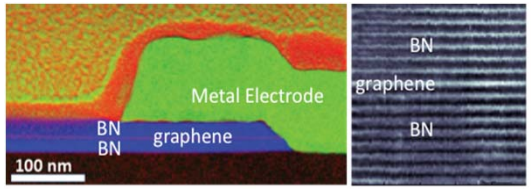


- Semiconducting materials: WSe_2, NbS_2, MoS_2, …
- Complex-metallic compounds : $TaSe_2$, TaS_2, …
- Magnetic materials: EuS_2, $EuSe_2$,…
- Superconducting: $NbSe_2$, $Bi_2Sr_2CaCu_2O_{8-x}$, ZrNCl,…

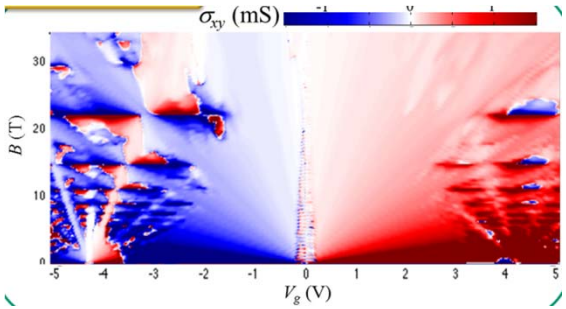


Outline

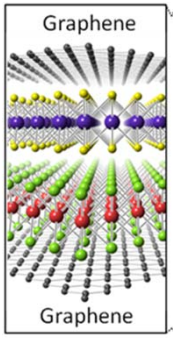
- Creating graphene based heterostructures

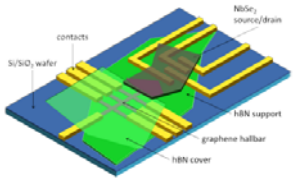


- SU(4) Integer, fractional and fractal quantum Hall effect



- Graphene and other 2D heterostructures

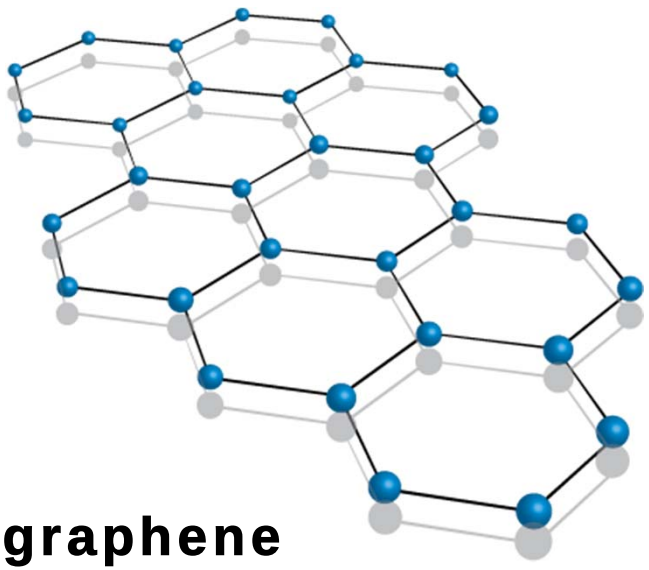




- Outlook

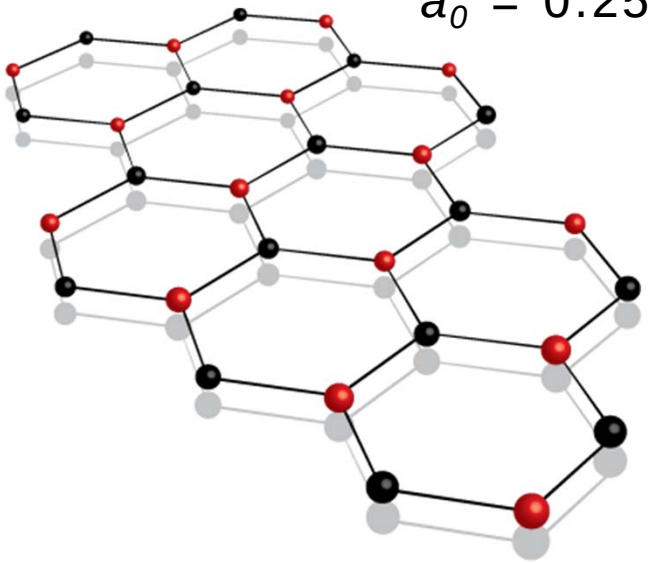
hexa Boron Nitride: Polymorphic Graphene

a_0 = 0.246 nm



graphene

a_0 = 0.250 nm



Boron Nitride

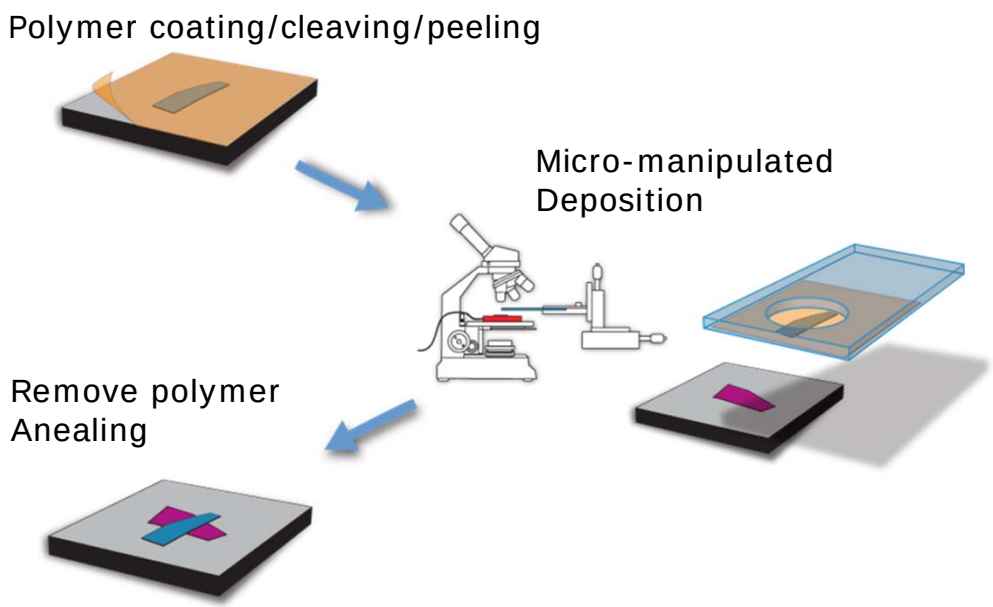
Comparison of h-BN and SiO_2

	Band Gap	Dielectric Constant	Optical Phonon Energy	Structure
BN	5.5 eV	~4	>150 meV	Layered crystal
SiO2	8.9 eV	3.9	59 meV	Amorphous

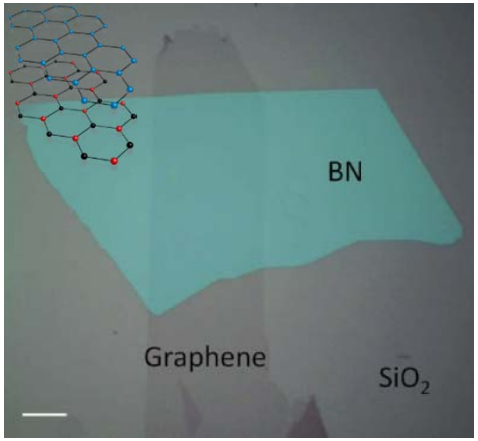
Stacking graphene on hBN

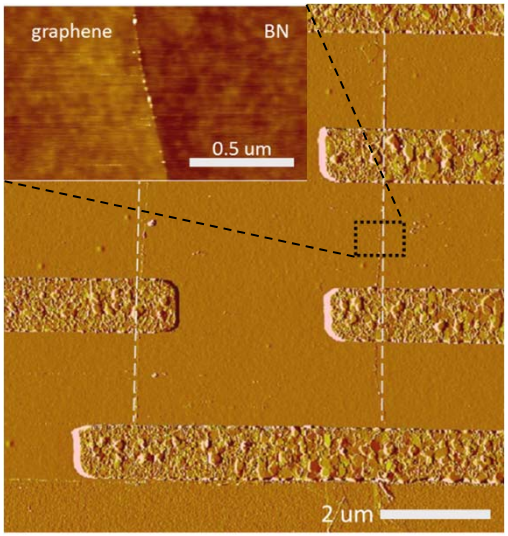
Dean et al. Nature Nano (2009)

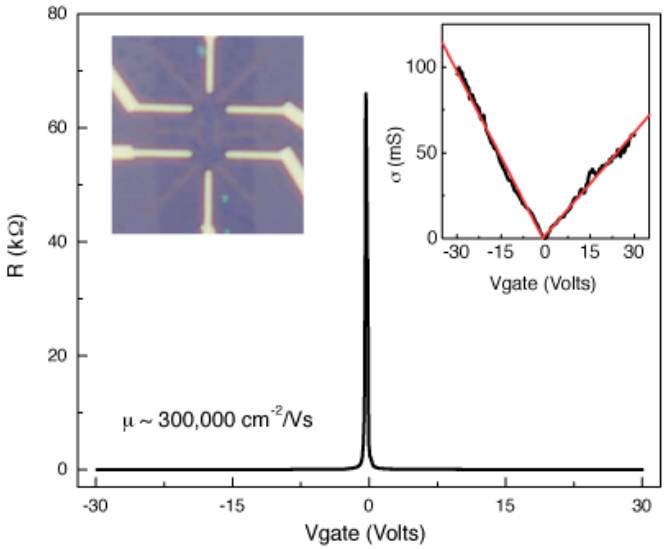
Hone, Kim and Shepard groups collaboration



- Co-lamination techniques
- Submicron size precision
- Atomically smooth interface



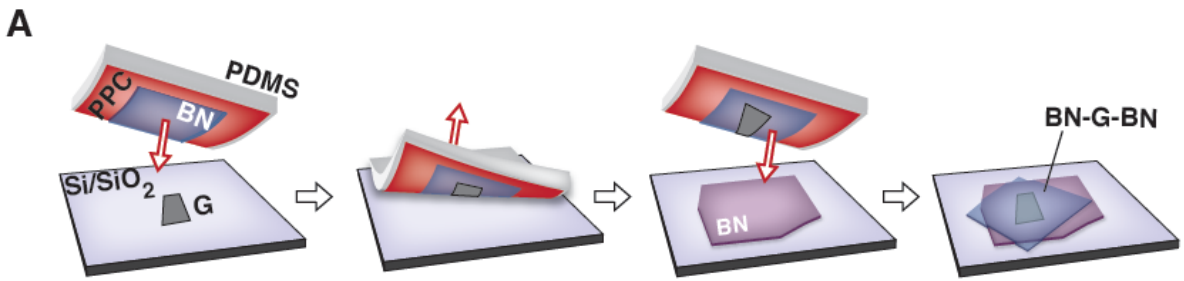


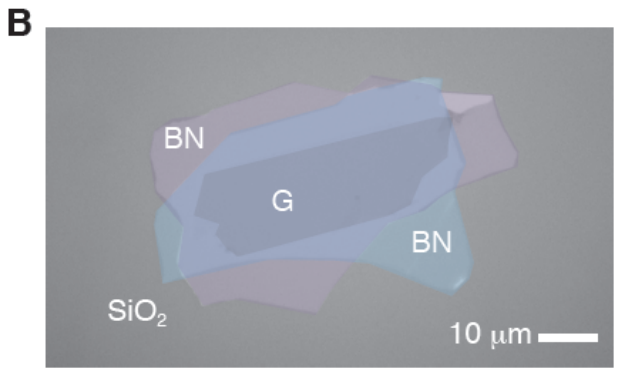


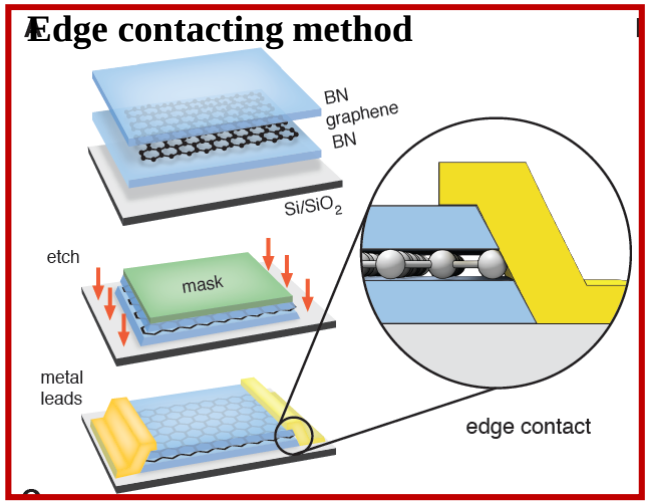
LT Mobility : ~300,000 $cm^2V^{-1}s^{-1}$

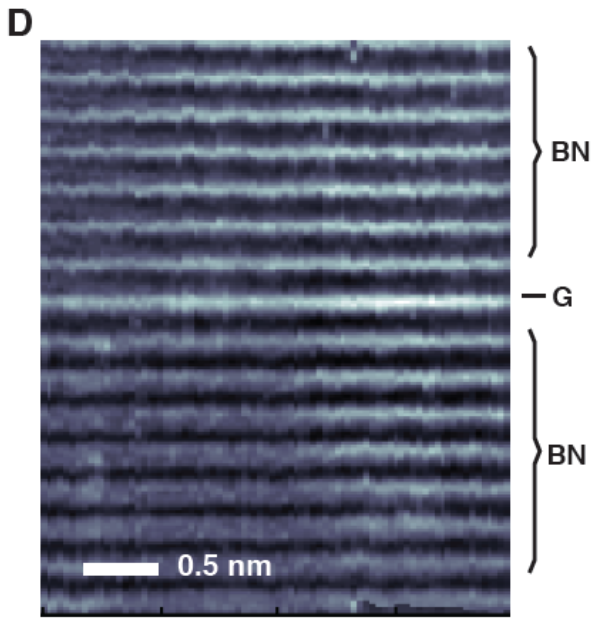
RT Mobility : ~100,000 $cm^2V^{-1}s^{-1}$

Pick-up Technique and Edge Contacts for Multilayer vdW Stacking (Columbia Team)



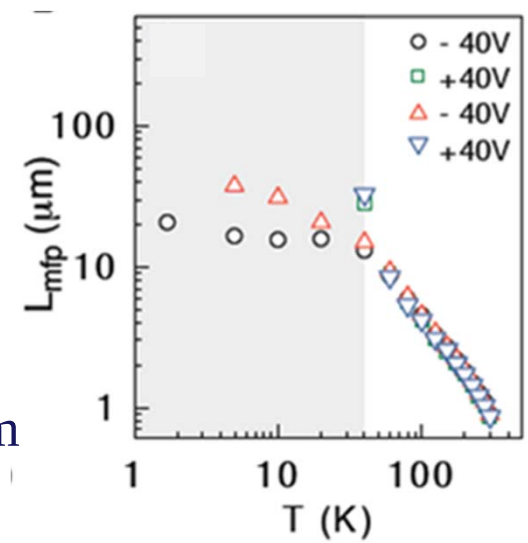






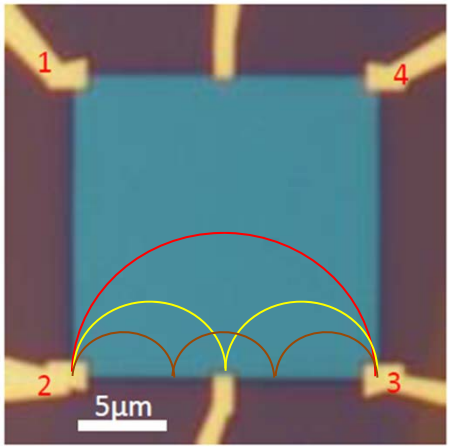
Contac Resistance: 100 Ω μm
Mobility ~ 10^6 $cm^2/Vsec$
Mean free path > 10 μm

- Creation of multilayer systems with co-lamination techniques
- Encapsulated graphene in hBN
- Completely ballistic at low temperature

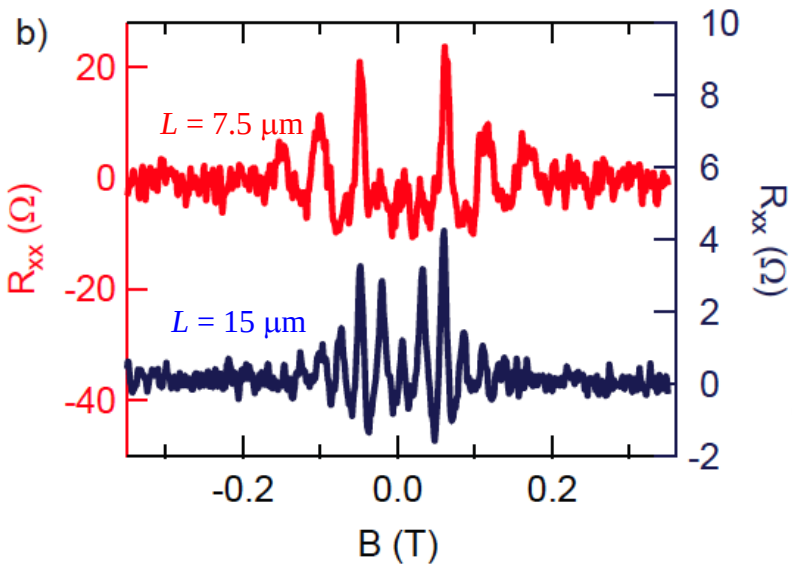


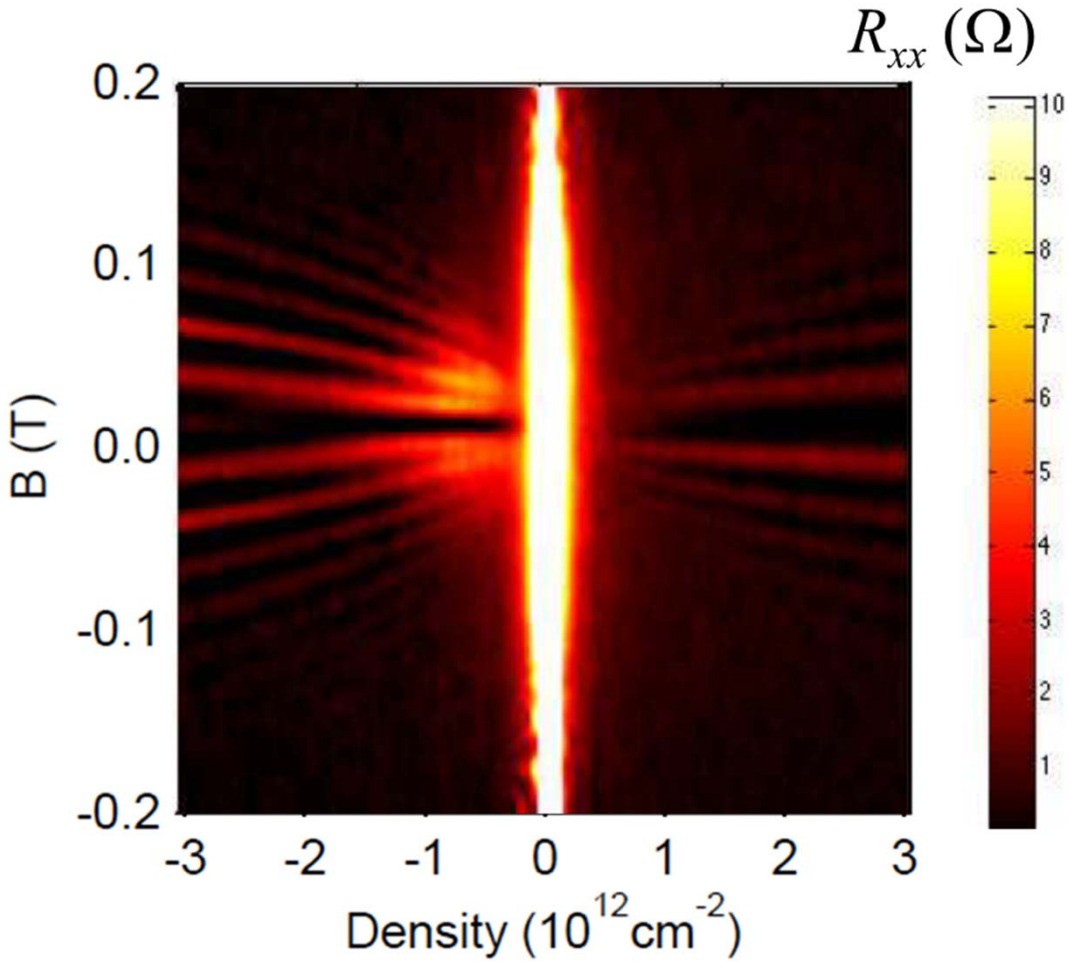
L. Wang *et al*, Science (2013)

Magnetic Focusing in Graphene



$$B^* = 2j\frac{\hbar\sqrt{\pi n}}{eL}$$

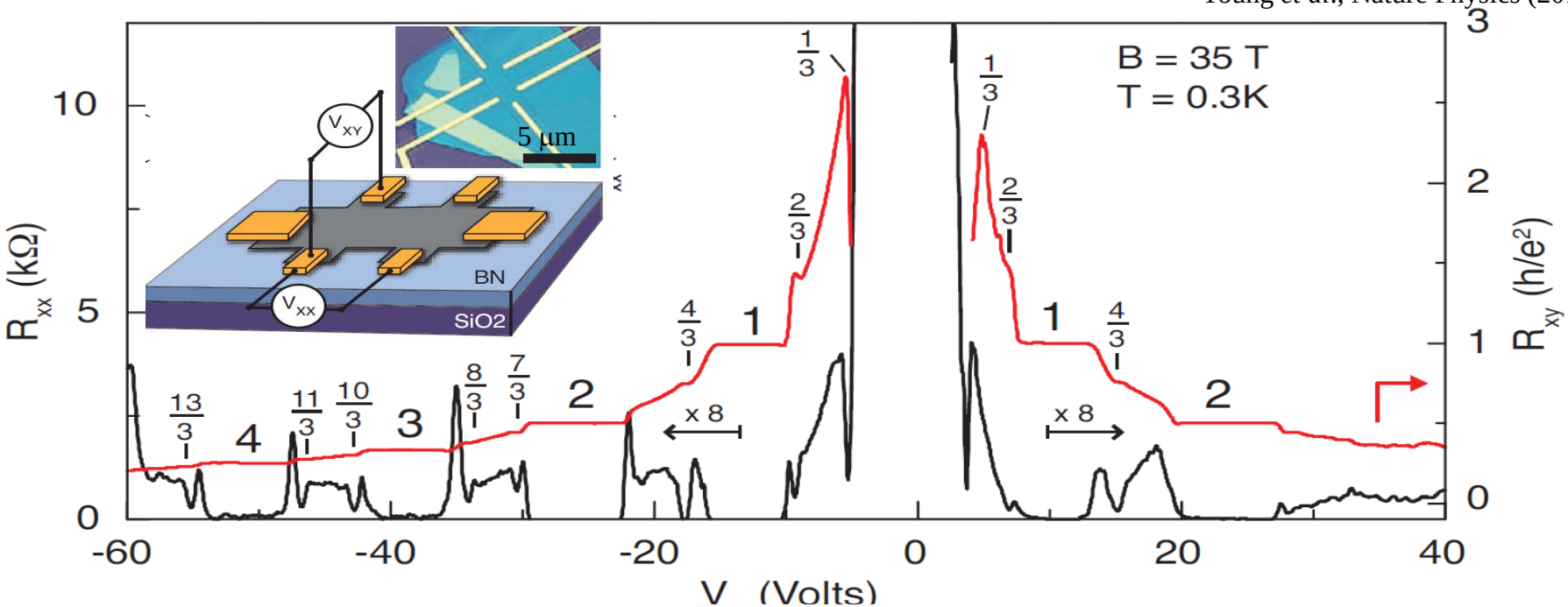




Similar result in Taychatanapat *et al*. (2013)

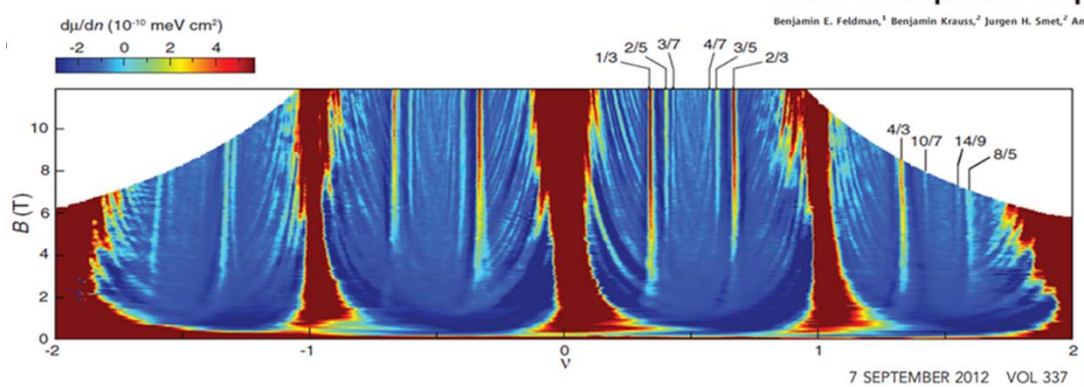
Integer and Fractional Quantum Hall Effect in Graphene

Dean *et al*. Nature Physics (2011)
Young *et al*., Nature Physics (2012)



Unconventional Sequence of Fractional Quantum Hall States in Suspended Graphene

Benjamin E. Feldman,[1] Benjamin Krauss,[2] Jurgen H. Smet,[2] Amir Yacoby[1*]

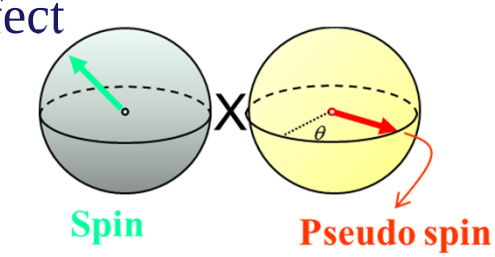


7 SEPTEMBER 2012 VOL 337 SCIENCE

ll Effect in single layer graphene

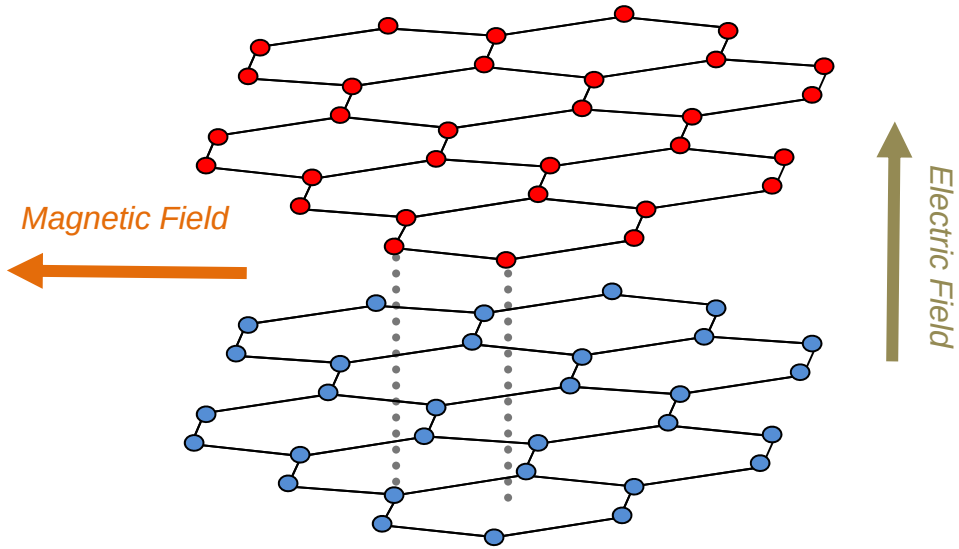
all Effect

ffect

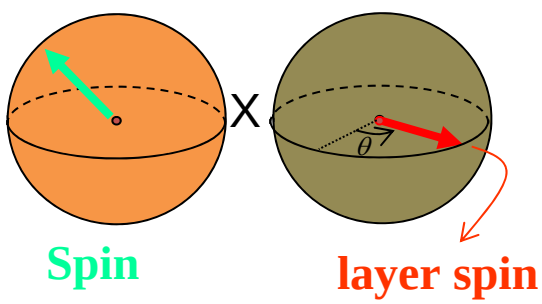


Pseudo Spin/ Valley Spin in Bilayer Graphene

Bilayer graphene



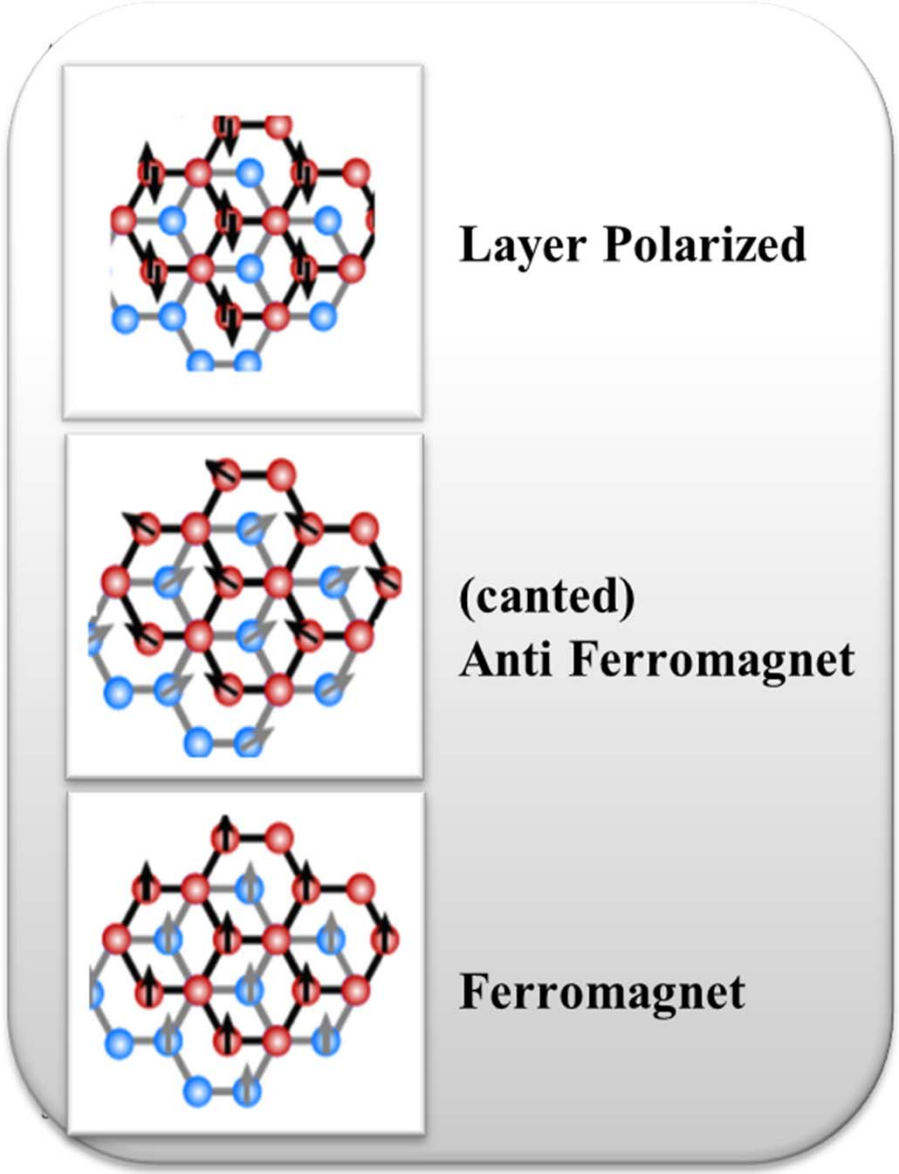
4-component wave function



$$\begin{bmatrix} \psi_{U\uparrow} \\ \psi_{U\downarrow} \\ \psi_{L\uparrow} \\ \psi_{L\downarrow} \end{bmatrix}$$

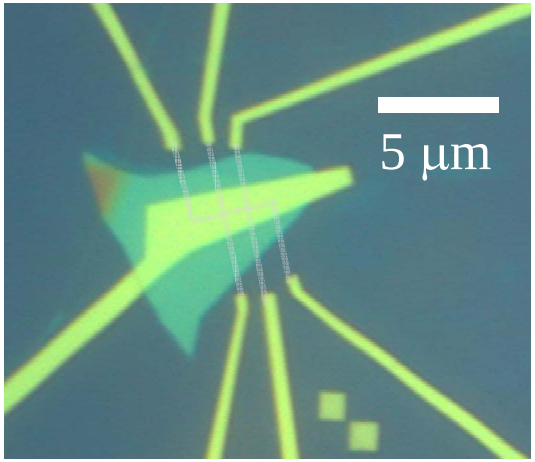
With perpendicular magnetic fields,
valley spin=layer spin = sub lattice spin

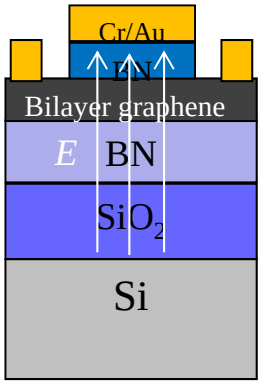
Possible Ground State at Charge Neutrality



Controlling Spin and Pseudo Spin in Bilayer

Doubly gated Bilayer graphene with BN dielectric



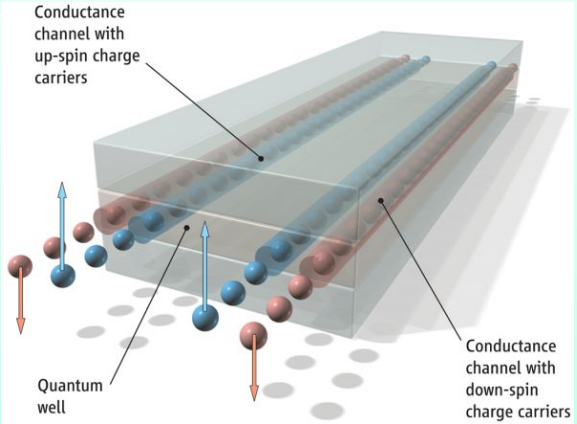


Electric field:
controlling layer pseudo spin

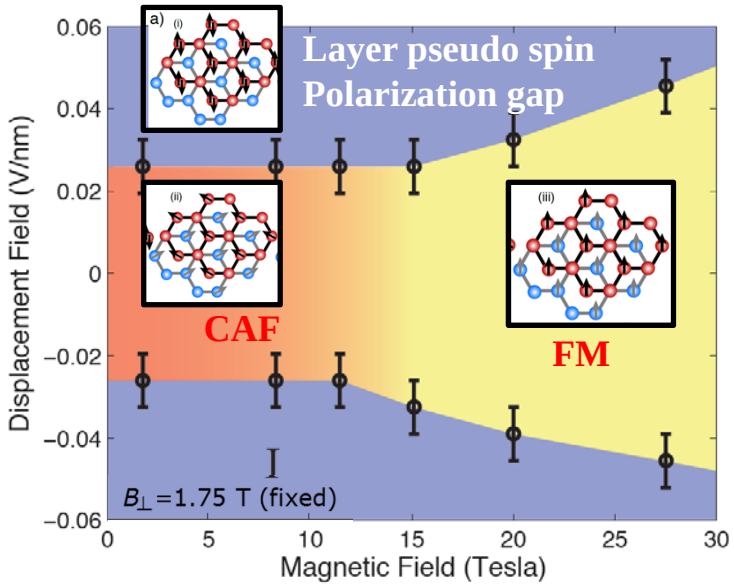
Magnetic Field:
Control Orbitals

Parallel magnetic field:
controlling spin

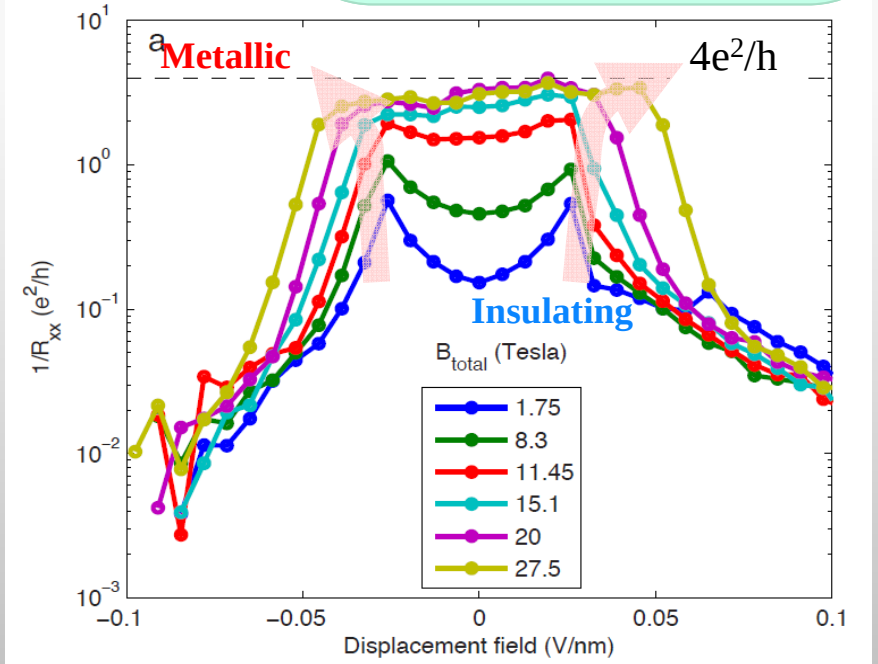
Analogical to Spin Quantum Hall State



M. König et al, Science (2007)



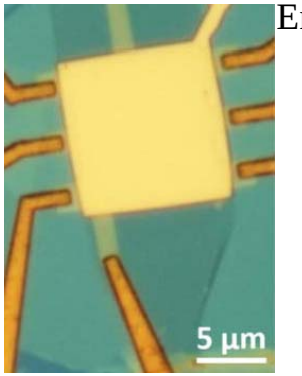
Cond



***B*⊥=1.75 T (fixed)** $n = 0$; $T = 0.35$ K

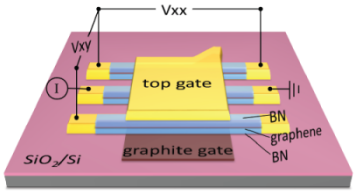
Phase Transitions Among Fractional Quantum Hall States

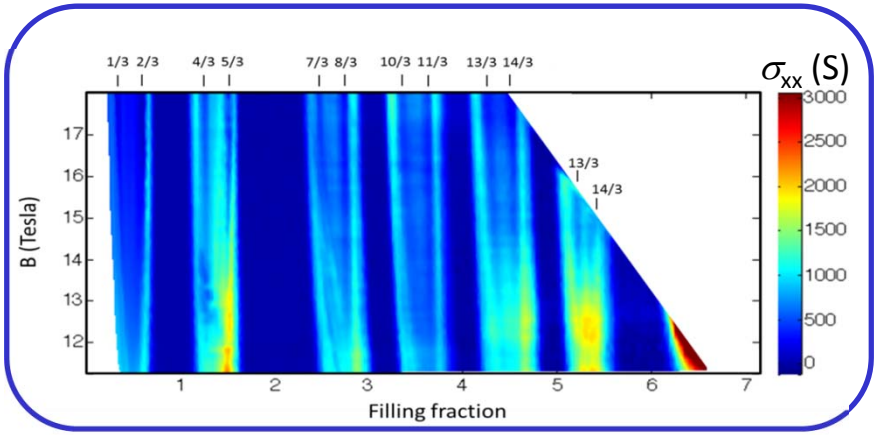
Bilayer Graphene



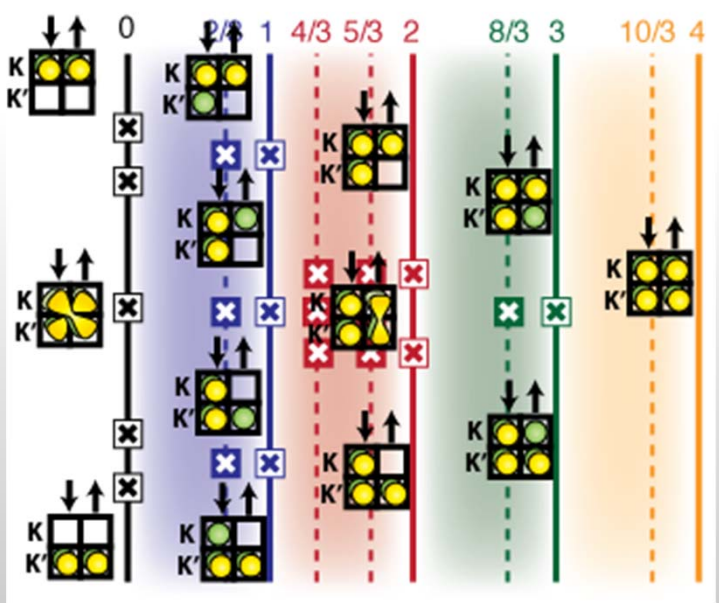
Encapsulated with top & bottom gate

mobility > 10^6 cm/Vsec



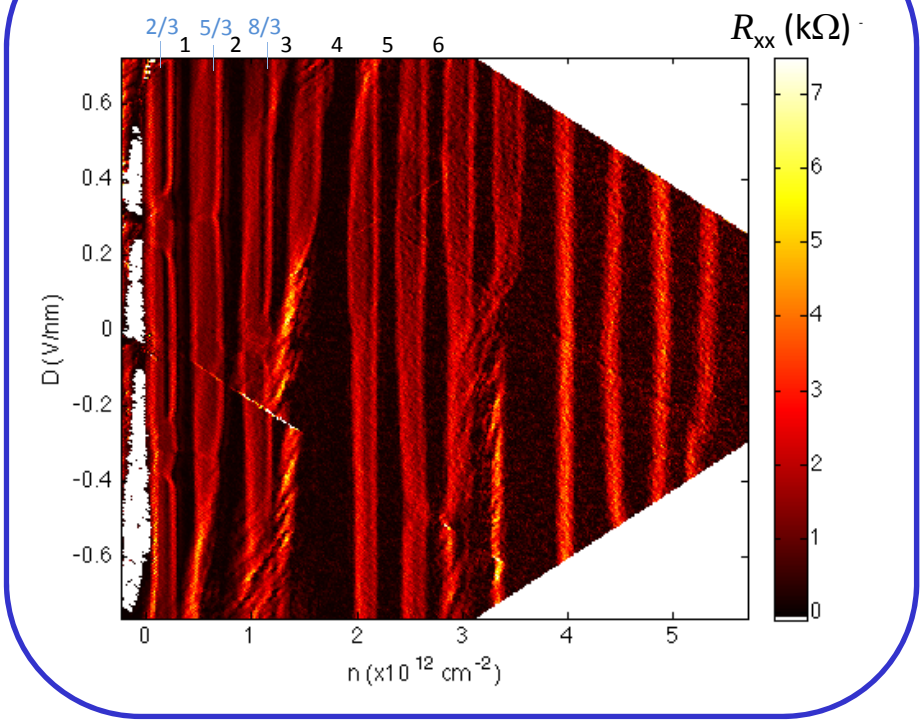


Phase Transitions in Lowest Landau Levels

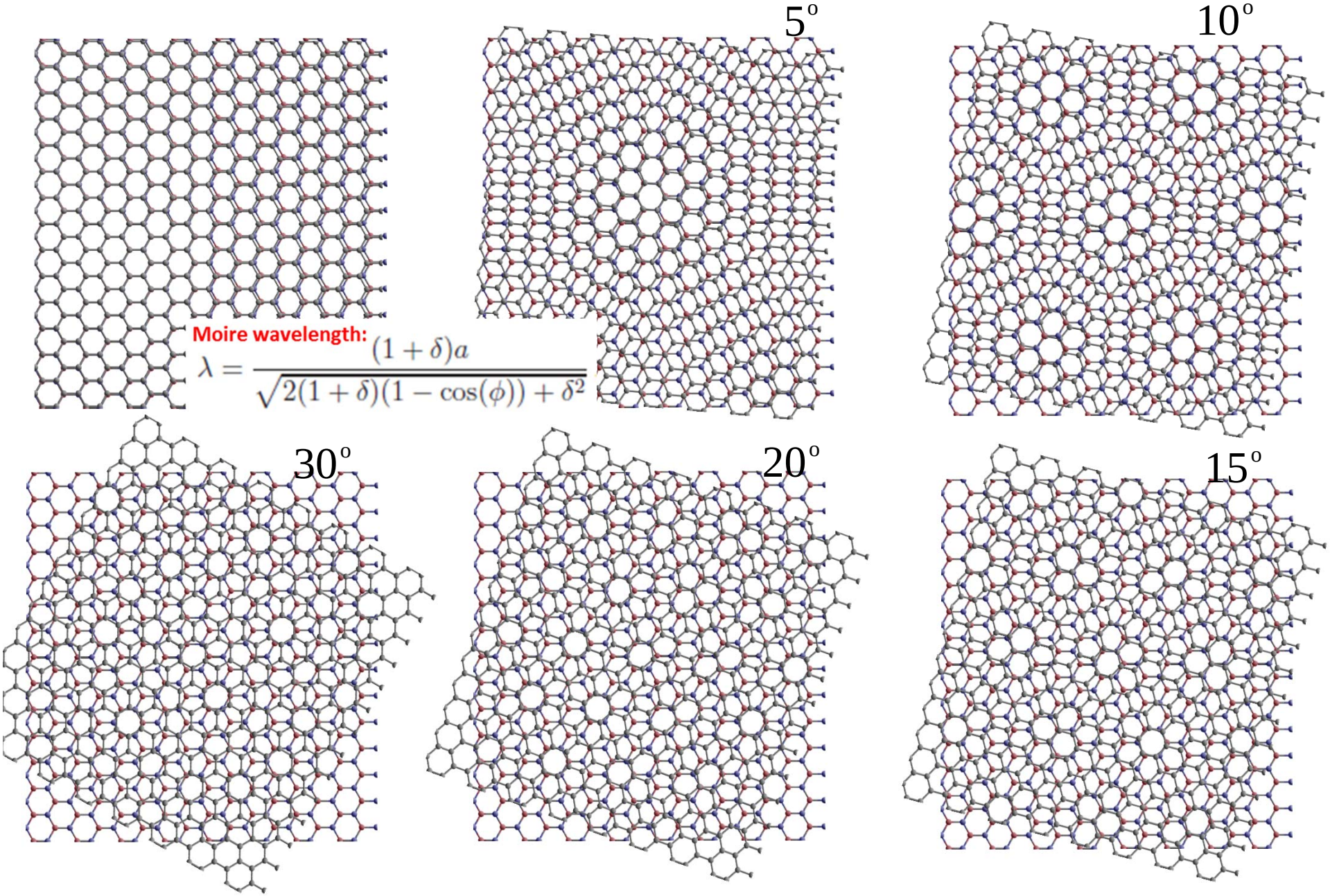


Maher*, Wang* *et al*. Submitted (2014)

E-field tunable FQHE



Graphen/hBN Moire Pattern

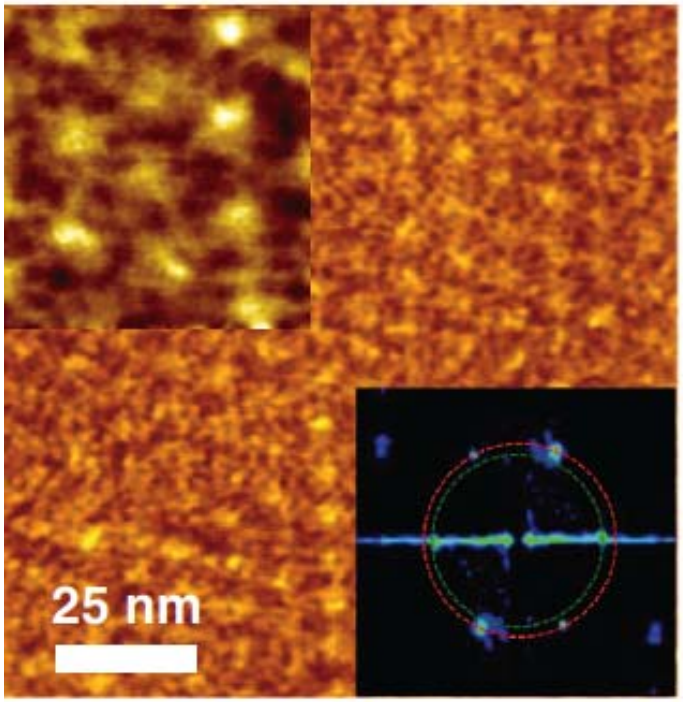


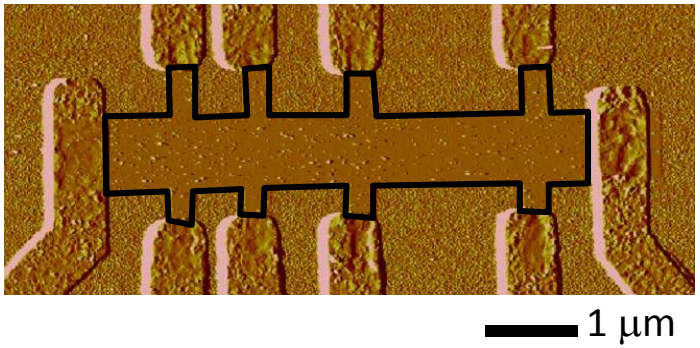
Moire wavelength:

$$\lambda = \frac{(1+\delta)a}{\sqrt{2(1+\delta)(1-\cos(\phi))+\delta^2}}$$

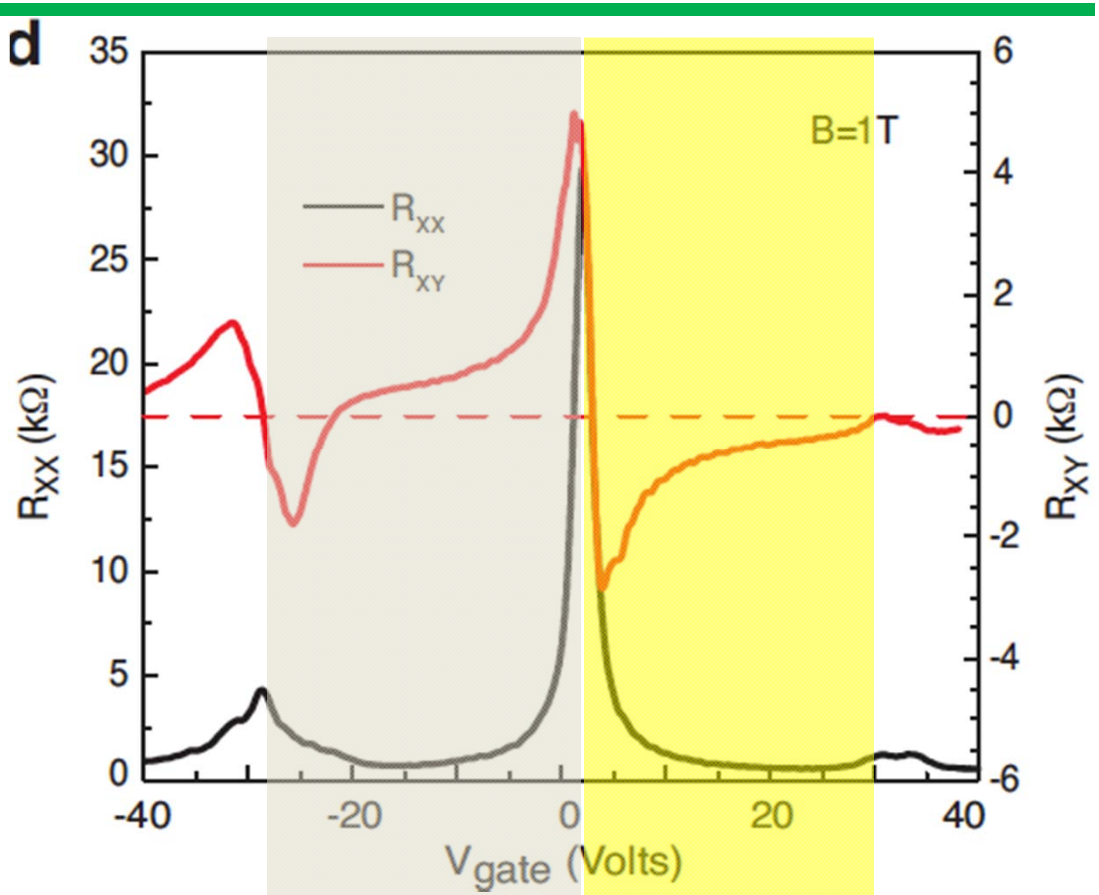
Bilayer Graphene on hBN: Moire Pattern

UHV AFM (Ishigami group)

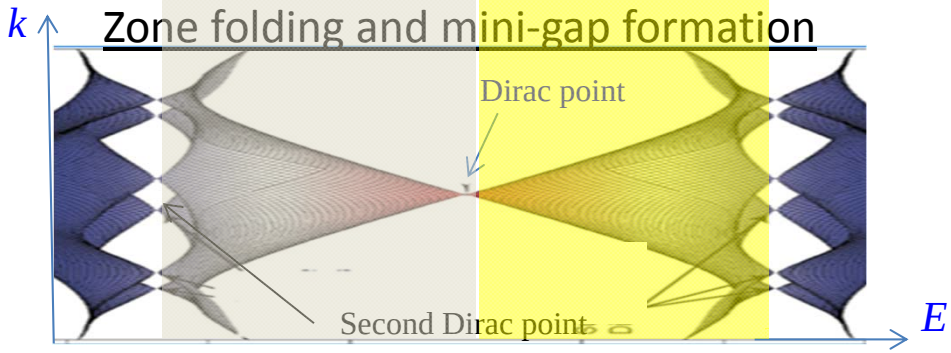




Moiré λ_{AFM} = 15.5 nm



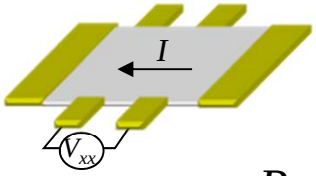
Zone folding and mini-gap formation

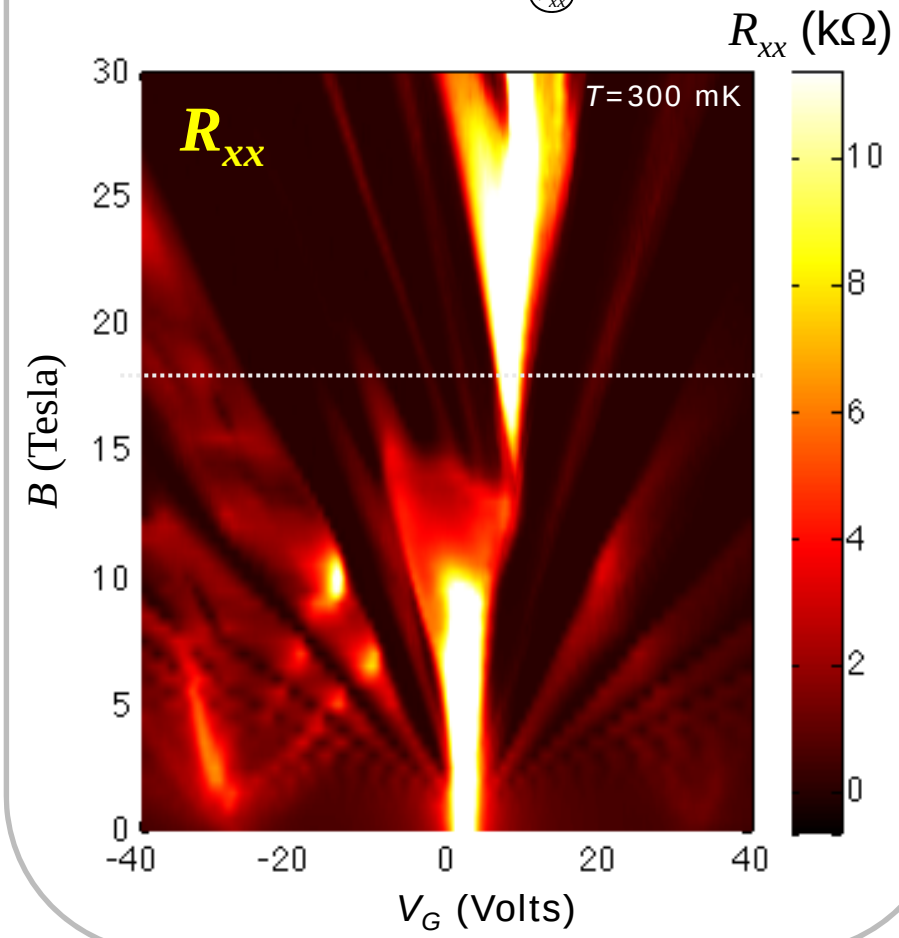


Quantum Hall Effect in Graphene Moire

Quantum Hall-like Transport

$$R_{xx} = \frac{V_{xx}}{I}$$





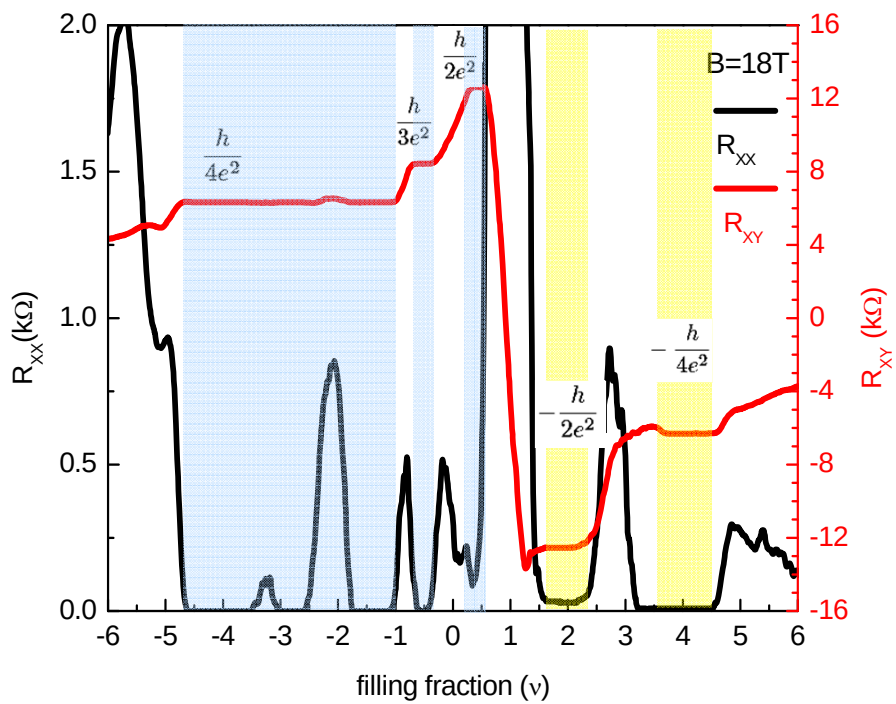
Landau level filling factor

$$\nu = \frac{\phi_0}{B} n$$

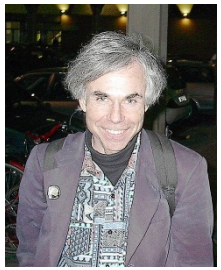
Quantum Hall conductance

$$R_{xy}^{-1} = \frac{e^2}{h} t$$

$$\cancel{\nu = t} \quad \in \mathbb{Z}$$



Hofstadter's Butterfly



PHYSICAL REVIEW B VOLUME 14, NUMBER 6 15 SEPTEMBER 1976

Energy levels and wave functions of Bloch electrons in rational and irrational magnetic fields*

Douglas R. Hofstadt
Physics Department, University of Oregon,
(Received 9 February 19

Quantum Hall Conductance

$$\sigma_{xy}^{Q} = ec\frac{\partial n(E)}{\partial B}\bigg|_{E=E_F} = \frac{e^2}{h}t$$

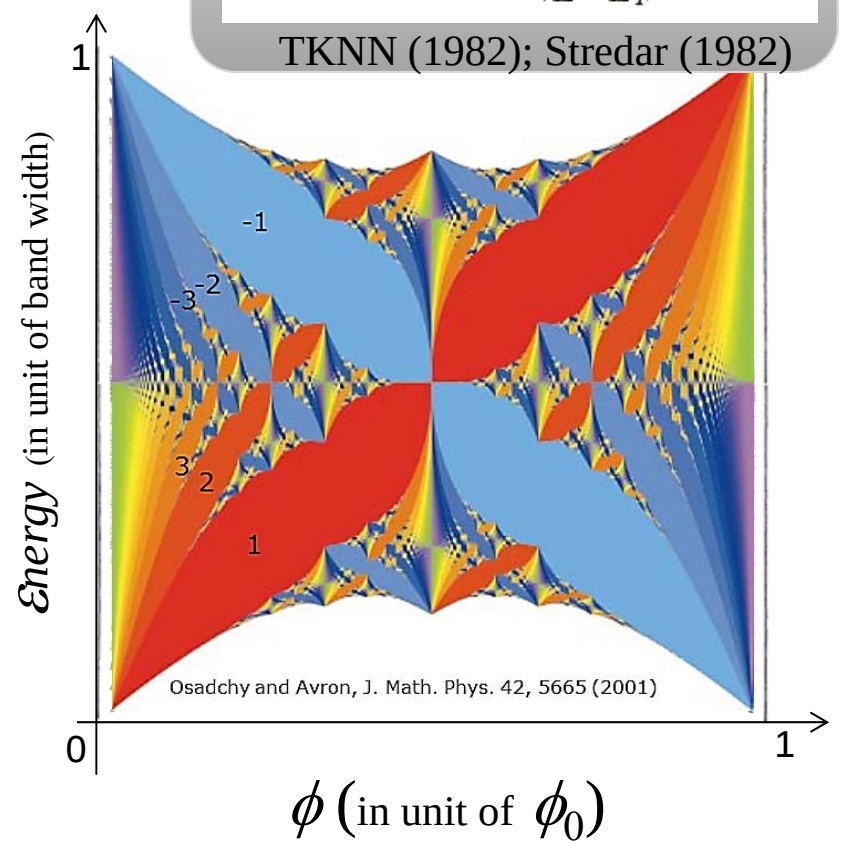
TKNN (1982); Stredar (1982)

Harper's Equation

$$2\psi_l \cos(2\pi l b - \kappa) + \psi_{l+1} + \psi_{l-1} = E\psi_l$$

When $b=p/q$, where p, q are coprimes, each LL splits into ***q sub-bands that are p-fold degenerate***

Energy bands develop ***fractal structure*** when magnetic length is of order the periodic unit cell



Diophantine equation for gaps

$$(n/n_0) = t(\phi/\phi_0) + s \qquad t, s \in \mathbb{Z}$$

Wannier (1978)

Fractal Quantum Hall Effect

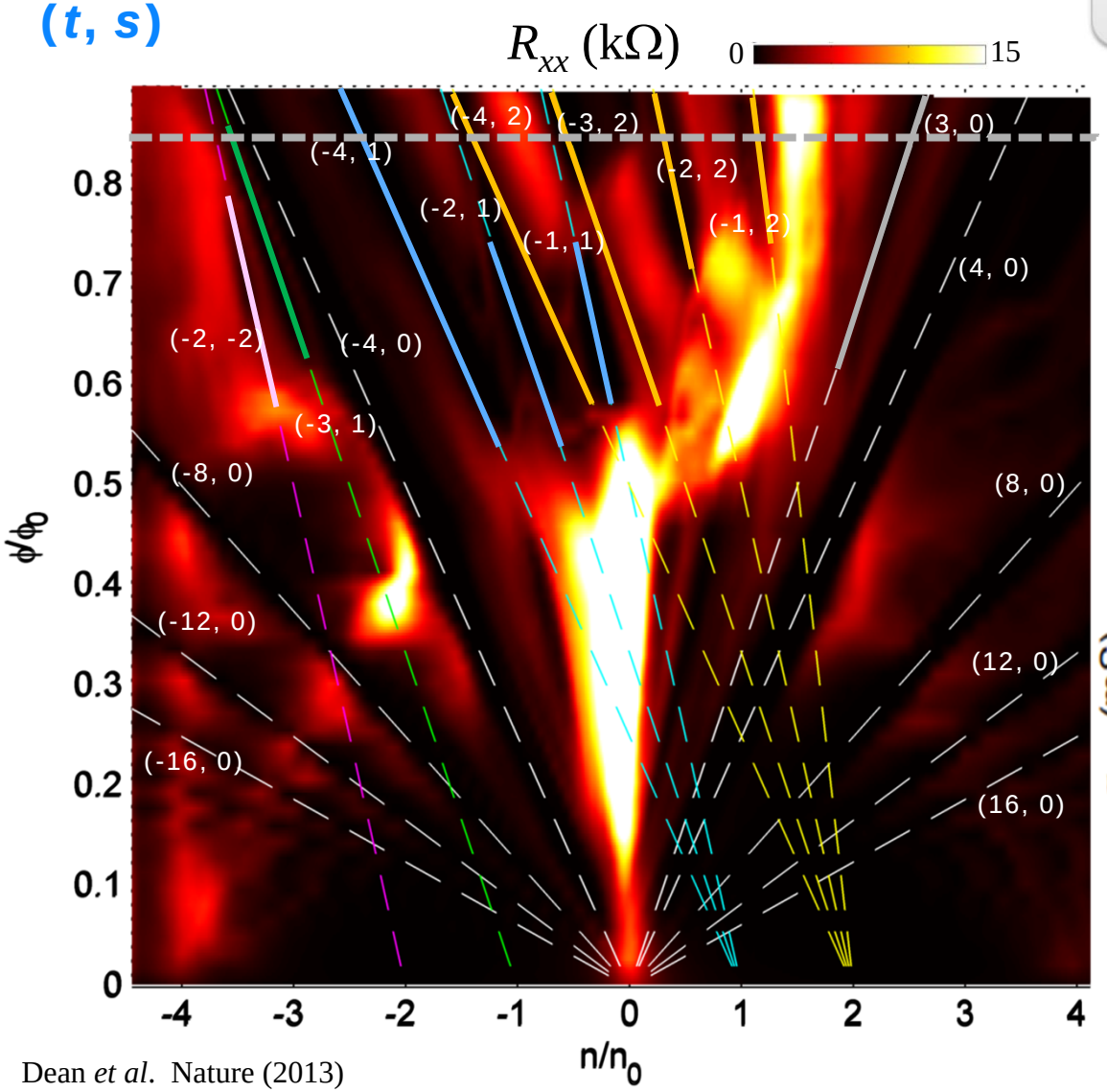
n/n_0: density per unit cell; ϕ : flux per unit cell

Diophantine equation for gaps

$$(n/n_0) = t(\phi/\phi_0) + s \qquad t, s \in \mathbb{Z}$$

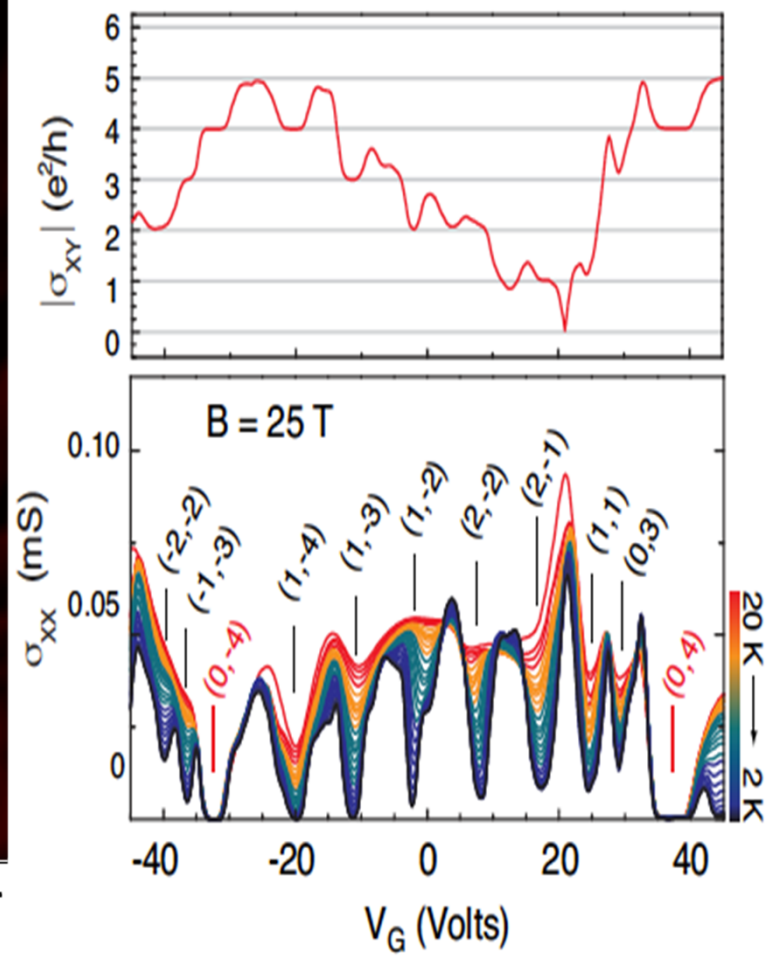
Wannier (1978)

(*t*, *s*)



Dean *et al*. Nature (2013)

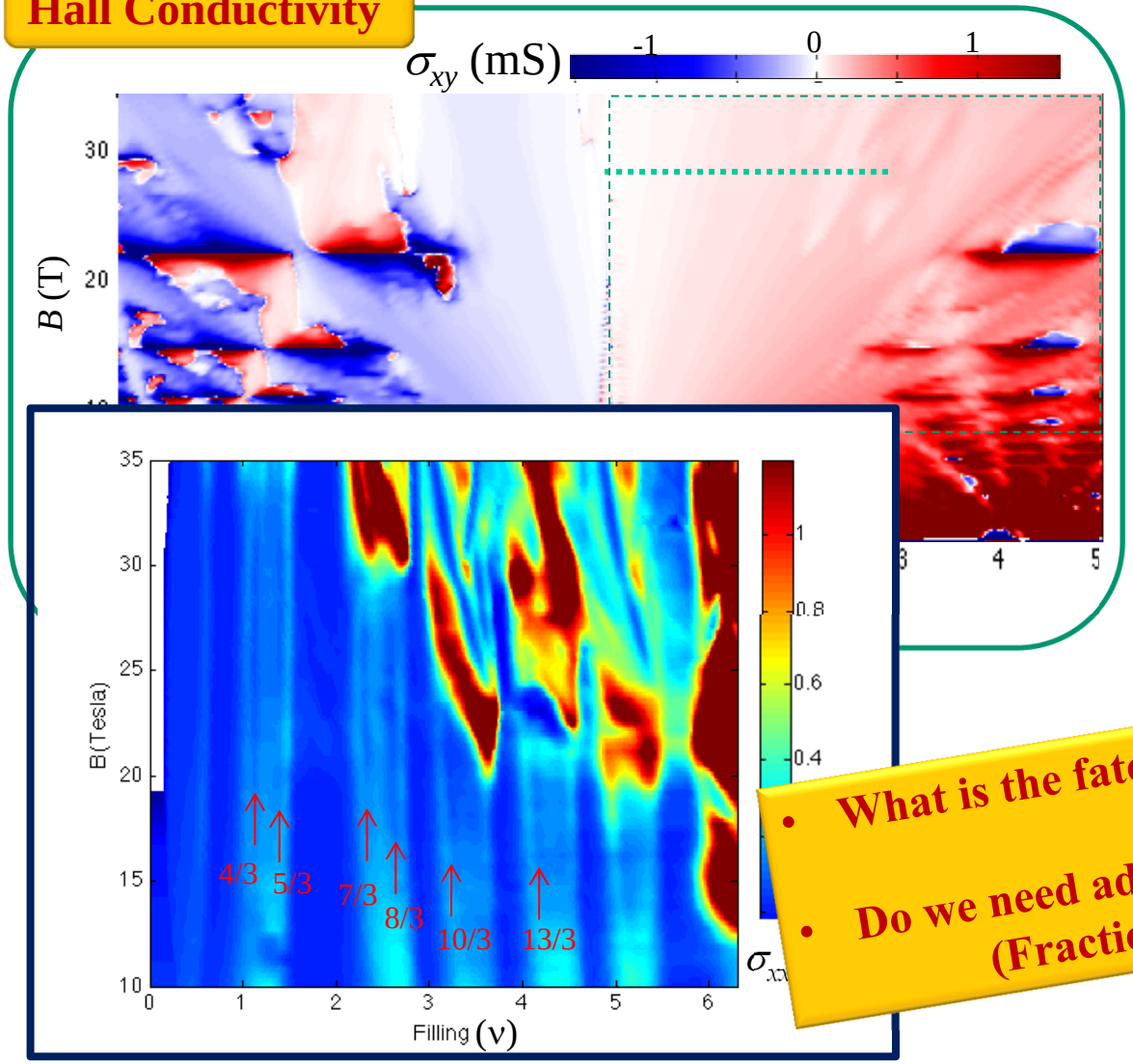
Quantization of σ_{xx} and σ_{xy}



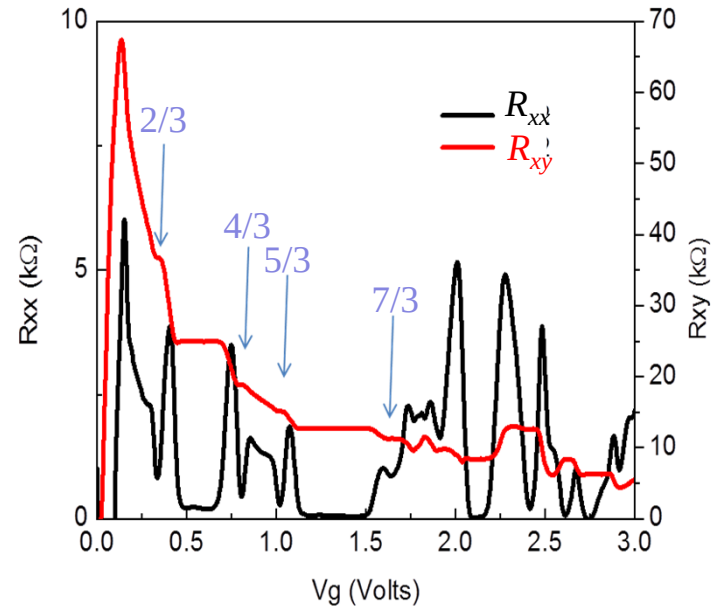
Fractional Quantum Hall Effect in Moire Superlattice

Single layer graphene on hBN @ 20 mK up to 35 T

Hall Conductivity



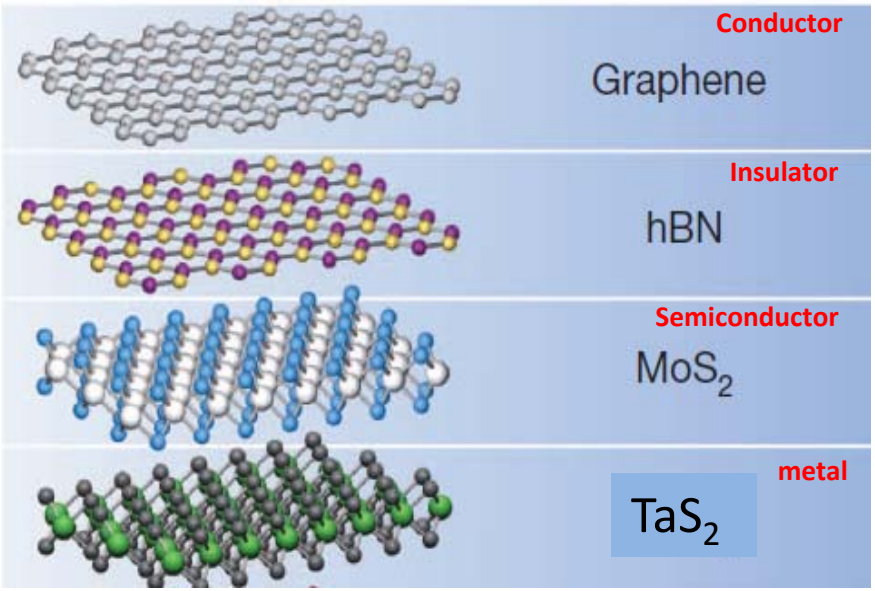
Fractional Quantum Hall Effect



- **What is the fate of FQHE in fractal spectrum?**
- **Do we need additional quantum numbers? (Fractional Fractal Quantum Hall Effect)**

In collaboration with C. Dean (CCNY)

Assembling van der Waals Materials

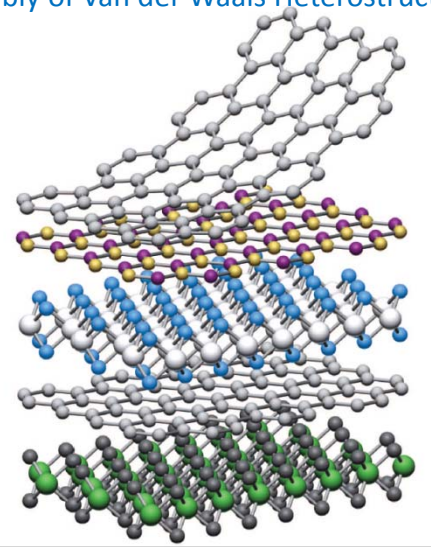


Geim (2013)

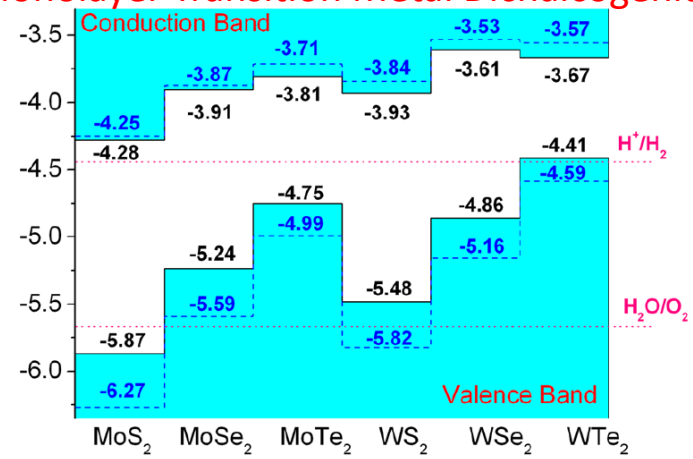
• • •

- Semiconducting materials: WSe_2, NbS_2, MoS_2, …
- Complex-metallic compounds : $TaSe_2$, TaS_2, …
- Magnetic materials: EuS_2, $EuSe_2$,…
- Superconducting: $NbSe_2$, $Bi_2Sr_2CaCu_2O_{8-x}$, FeSe,…
- Topological Insulator: Bi_2Se_3, Bi_2Te_3

Assembly of Van der Waals Heterostructures



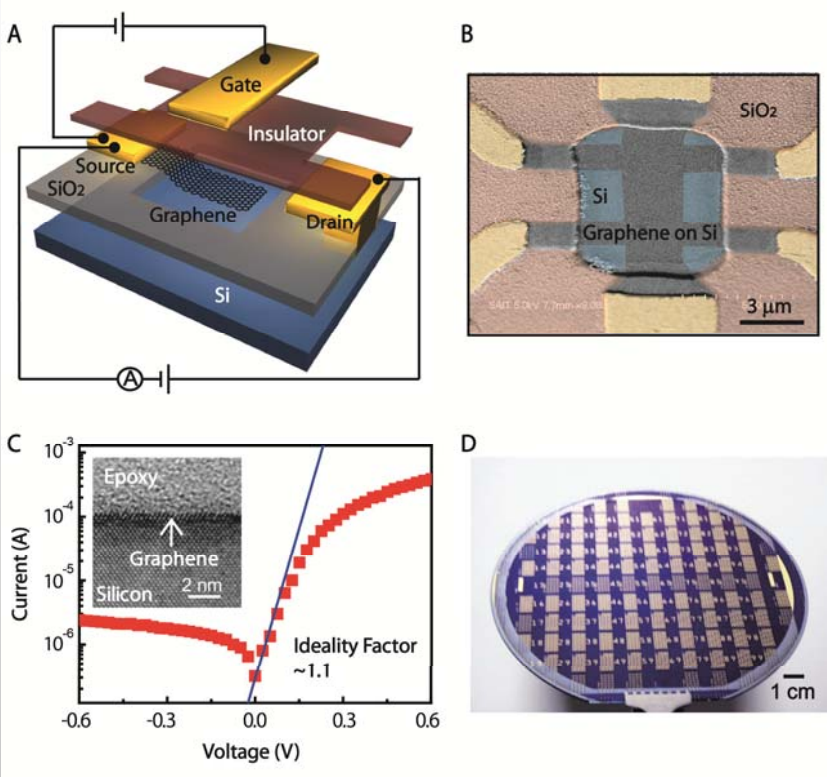
Energy Band Diagram of Monolayer Transition Metal Dichalcogenide

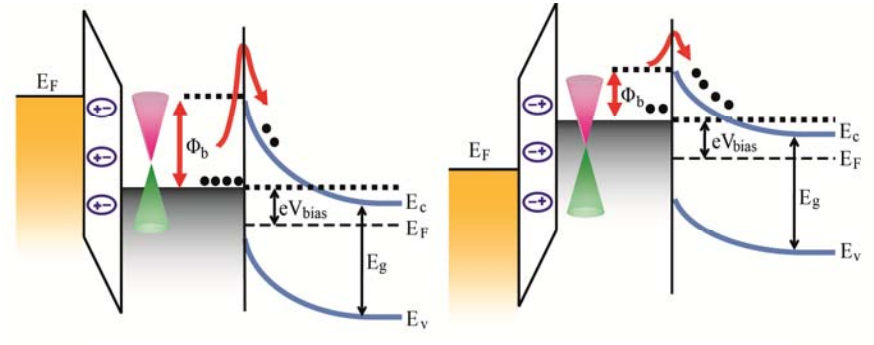


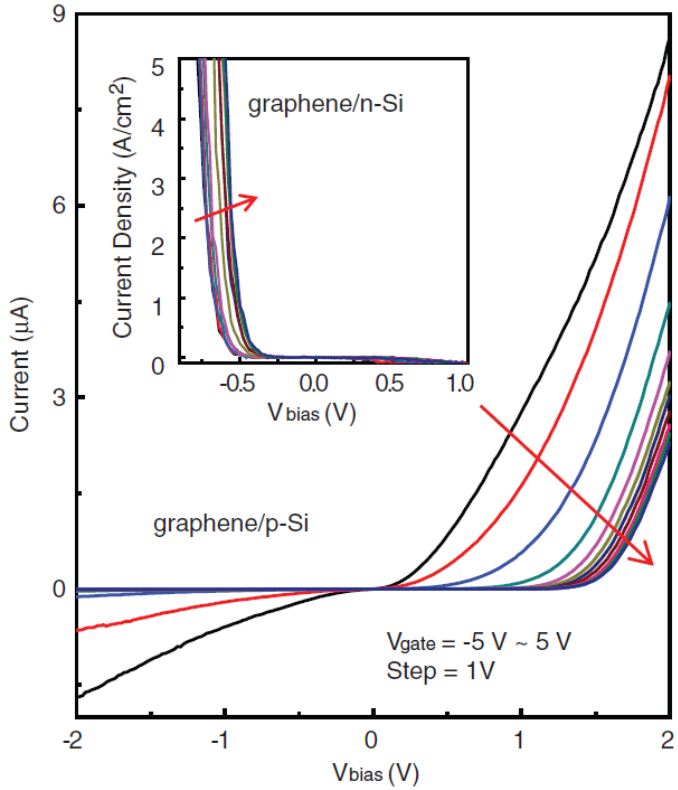
Appl. Phys. Lett. 102, 012111 (2013)

Graphene/Silicon hybrid Device: Graphene Barristors

Gate Variable Schottky Diode

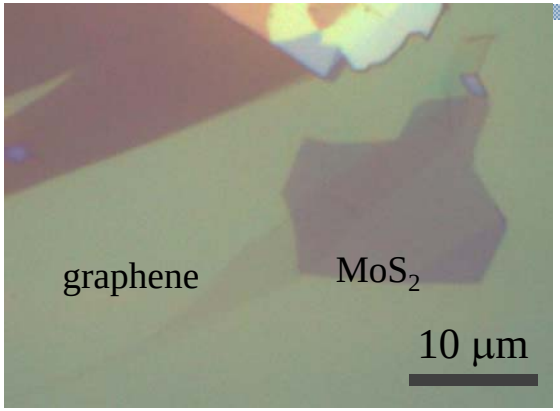


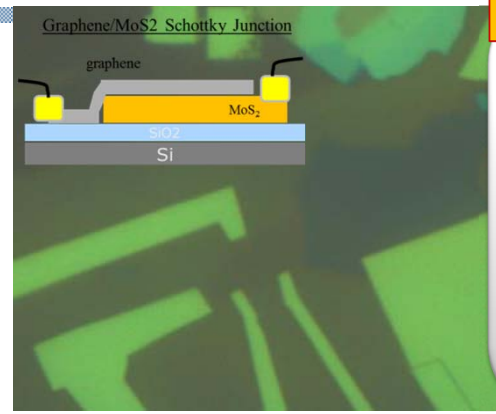


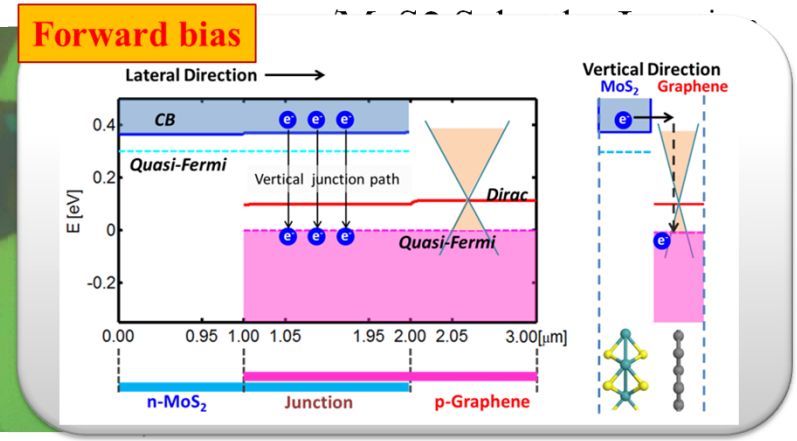


Yang *et al*. (SAIT collaboration) Science 336, 1240 (2012)

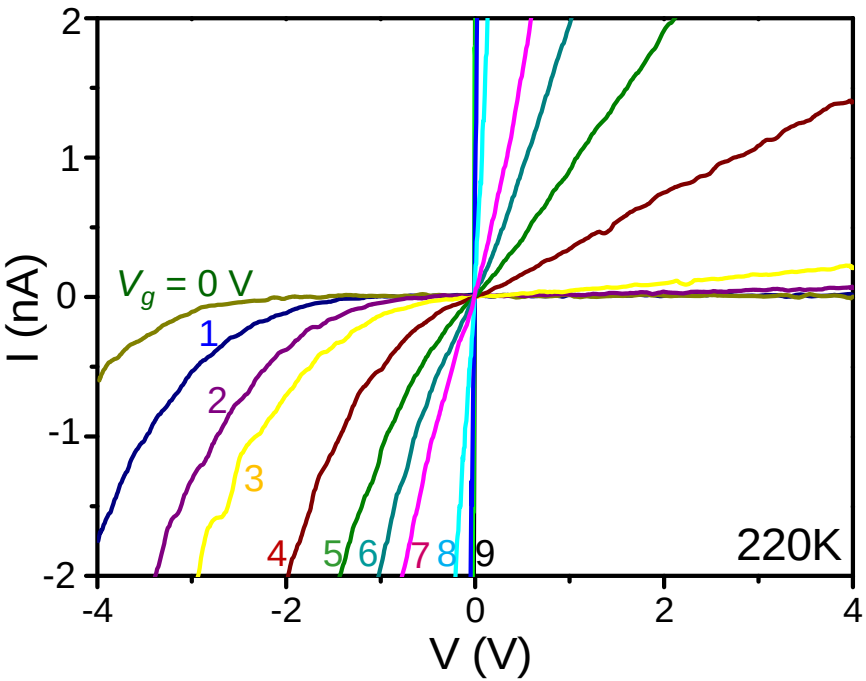
MoS_2 / graphene Heterojunction



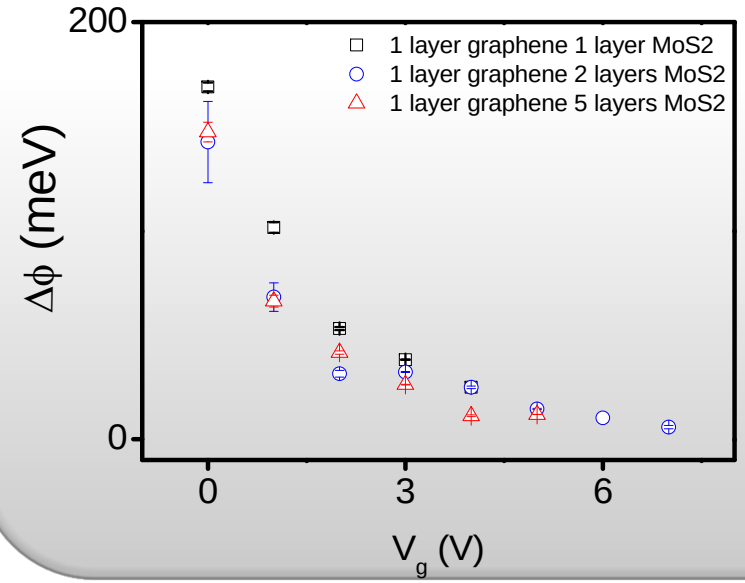




Gate tunable MoS2/graphene junction



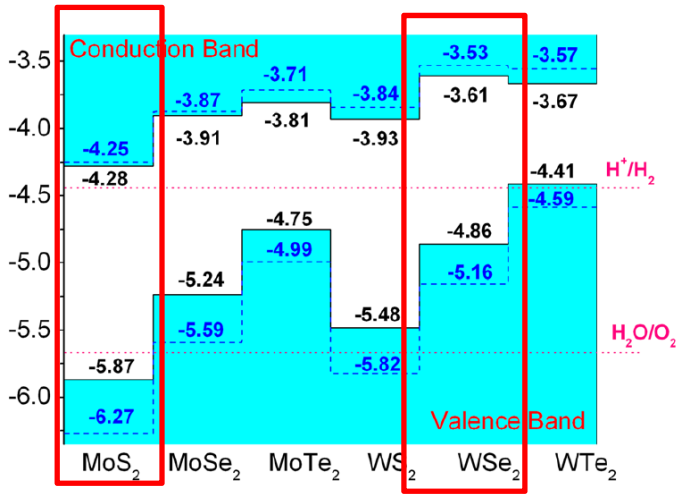
Schottky Barrier Versus Gate Voltage

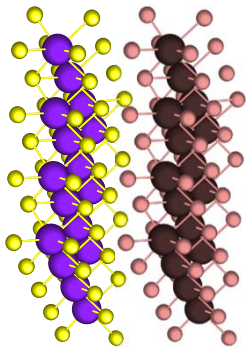


Barreiro *et al*. in preparation (2014)

Atomically Thin vdW p-n junction

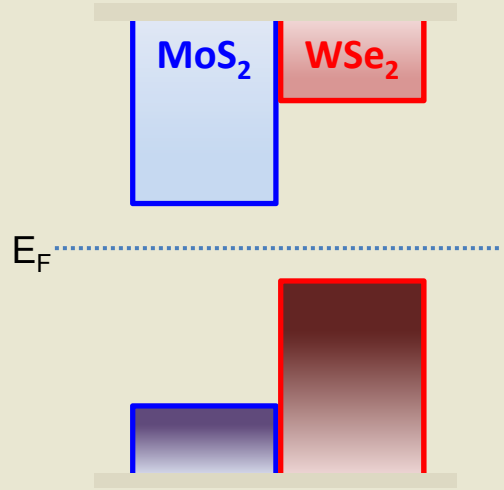
Band gaps and alignment of vdW semiconductors





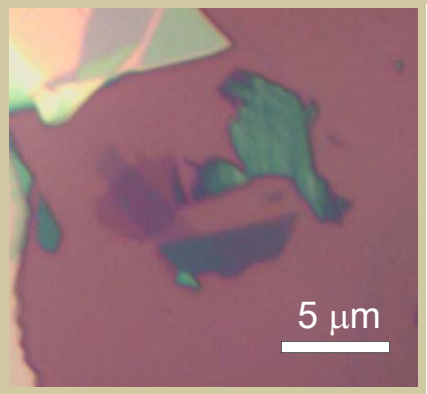
Appl. Phys. Lett. **102**, 012111 (2013)

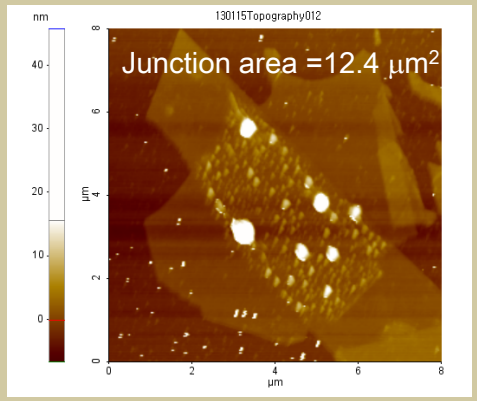
- **Type II semiconductor heterostructures**

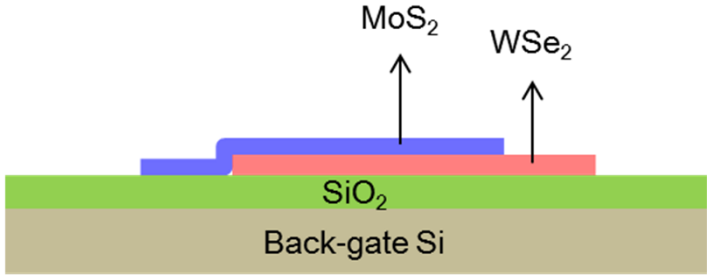


→ Tuning the diode & photovoltaic effect ?

Monolayer WSe_2-MoS_2 heterostructure

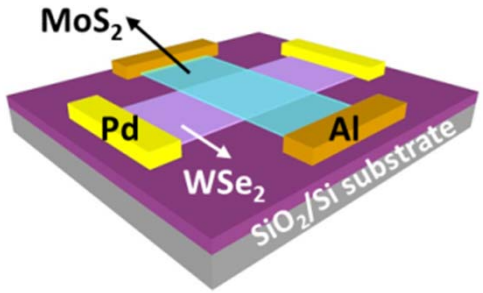


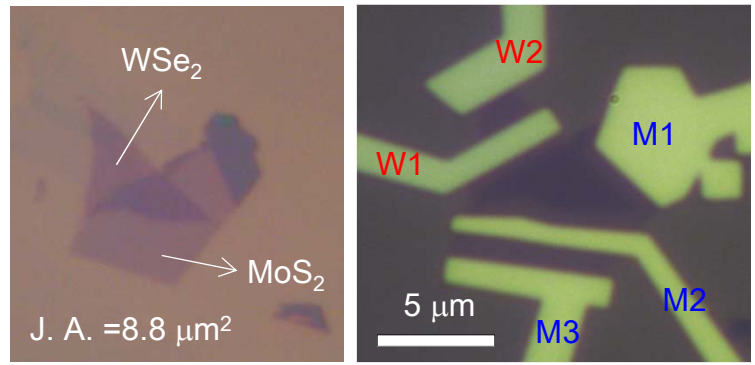




Atomically Thin PN junction: MoS_2/WSe_2

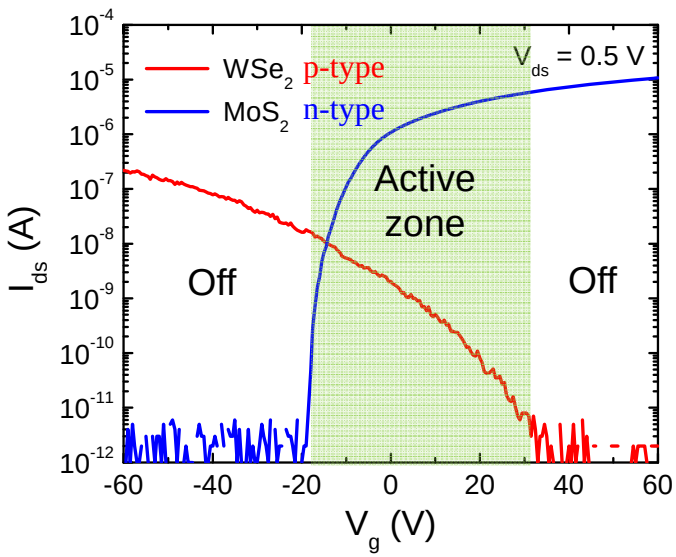
Vertical & Lateral Channels

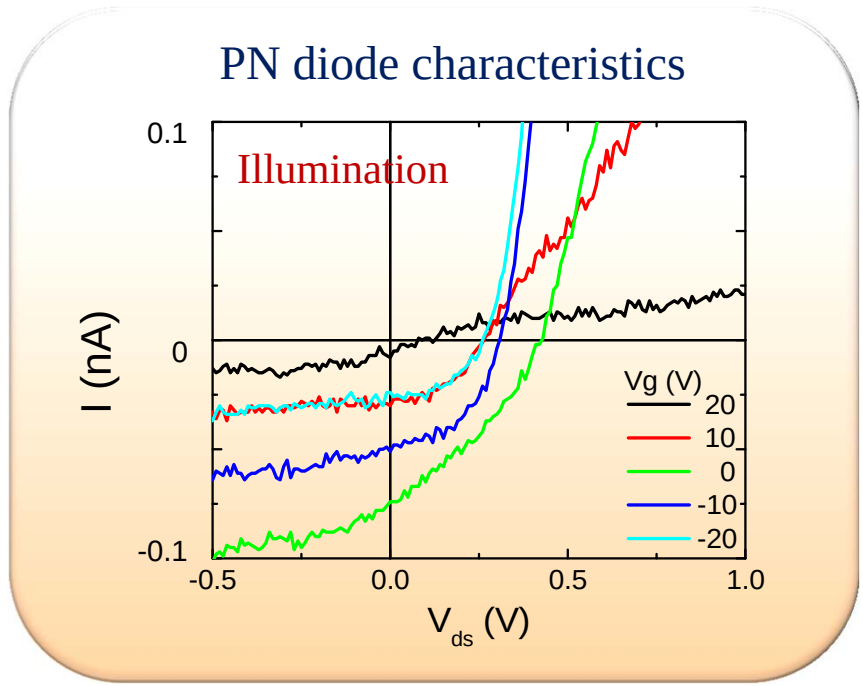




- Al contact to MoS_2 for electron injection
- Pd contact to WSe_2 for hole injection

Field Effect Transistor Characteristics



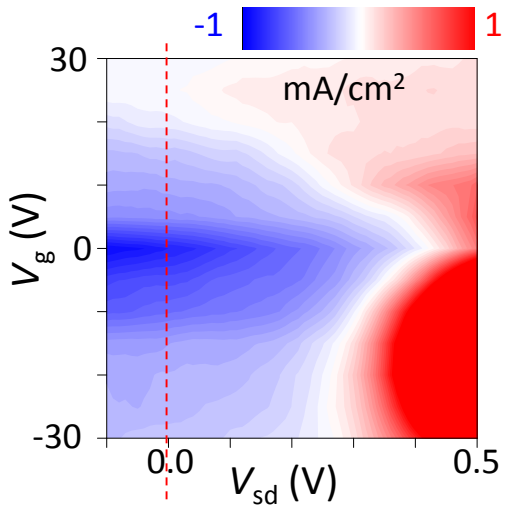


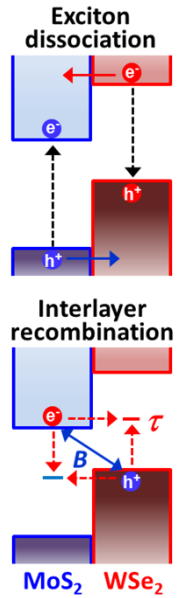
Atomically thin tunable photovoltaic cell!

C. Lee *et al*. submitted (2014)

Gate Tunable Photovoltaic Characteristic

Gate dependent photodiode current





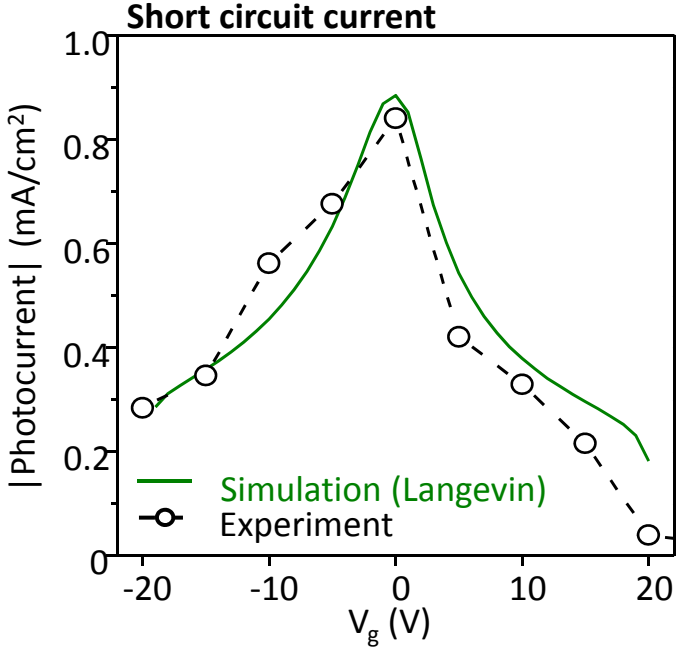
Shockeley-Read-Hall Recombination

$$R = \frac{1}{\tau}\frac{n_M p_W}{n_M + p_W}$$

Langevine Recombination

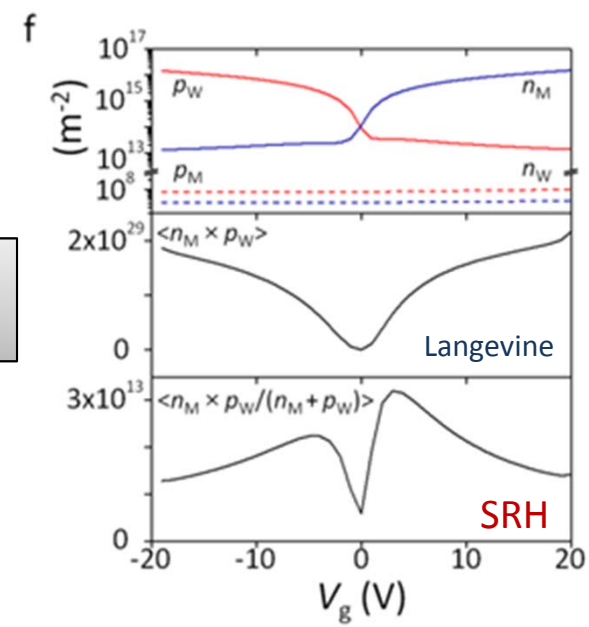
$$R = B\, nM\, p_W$$

Short circuit current

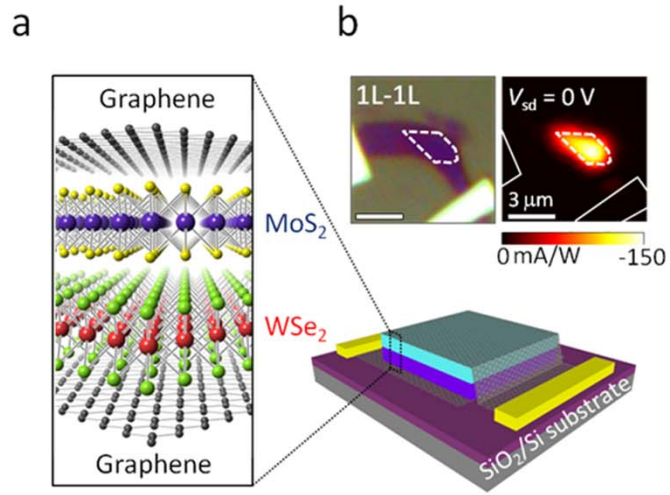


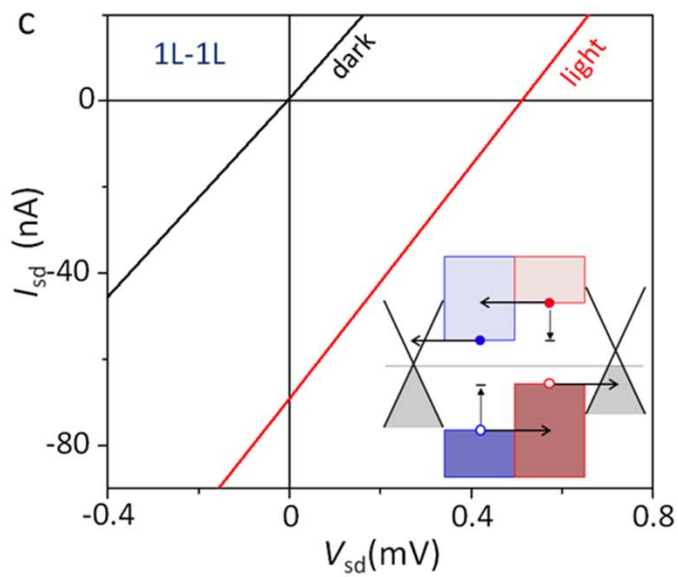
Short circuit current
= Generation - Recombination

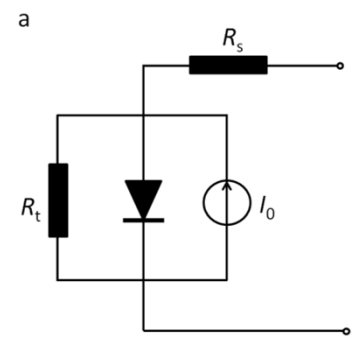
Langevine (Coulomb mediated) seems to be better match

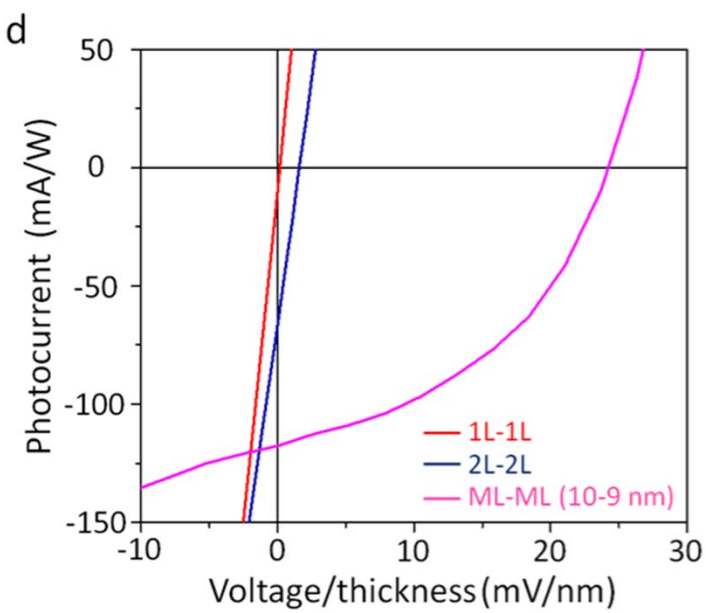


Vertical PN junction with Graphene vdW Electrodes





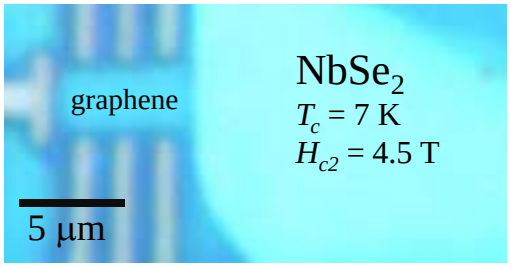


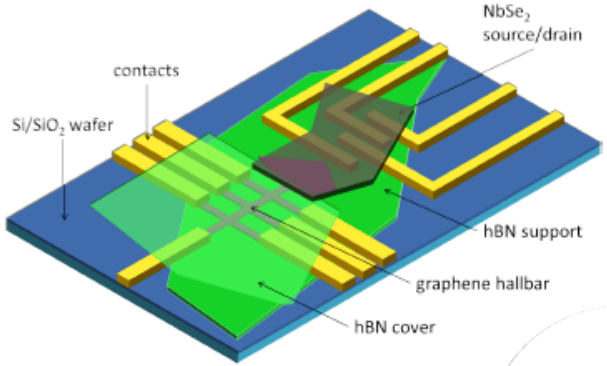


- Constructing graphene electrodes for efficient charge extraction via elastic tunneling
- Increased (x 3) photo current compared to the lateral junction
- Large parallel direct tunneling between graphene electrodes
- Increasing layer number reduce the tunneling current restoring the diode-like rectifying behaviors

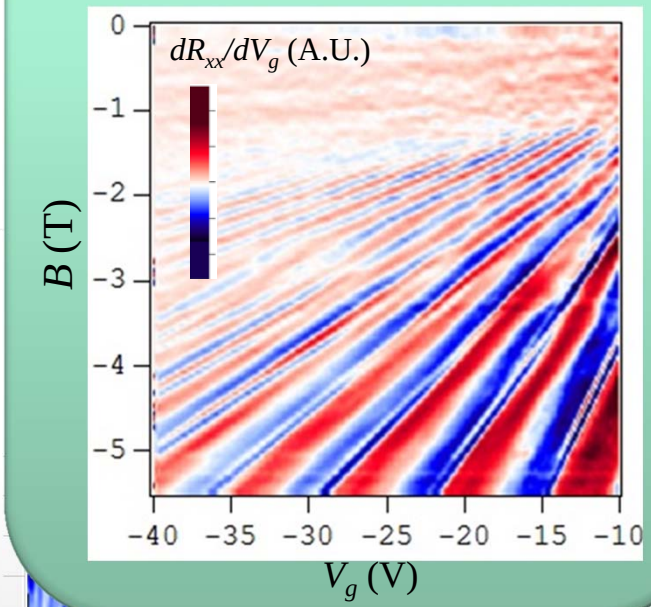
Andreev Reflections – between $NbSe_2$ & Graphene

Efetov *et al*. in progress (2014)

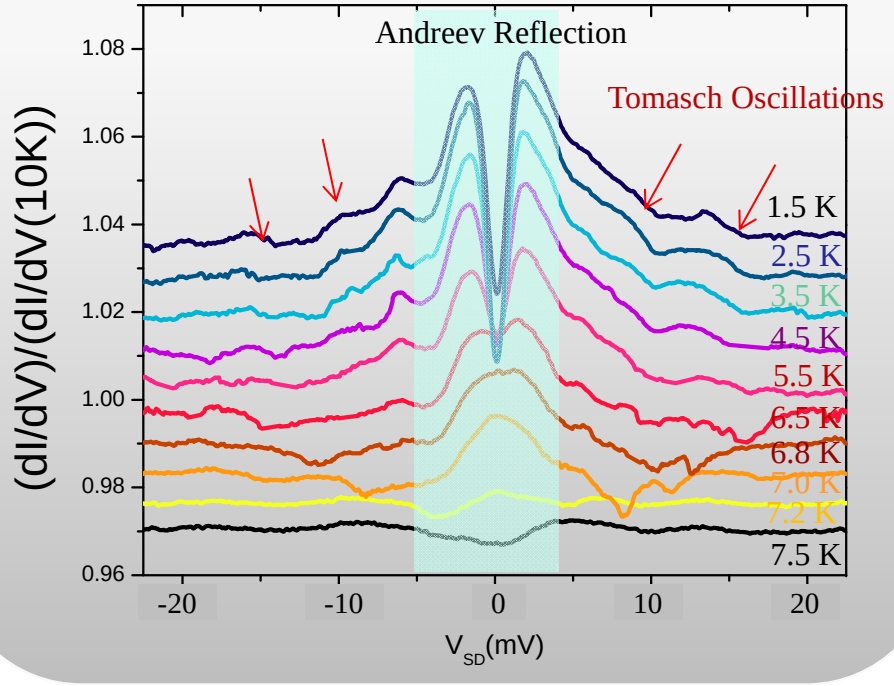


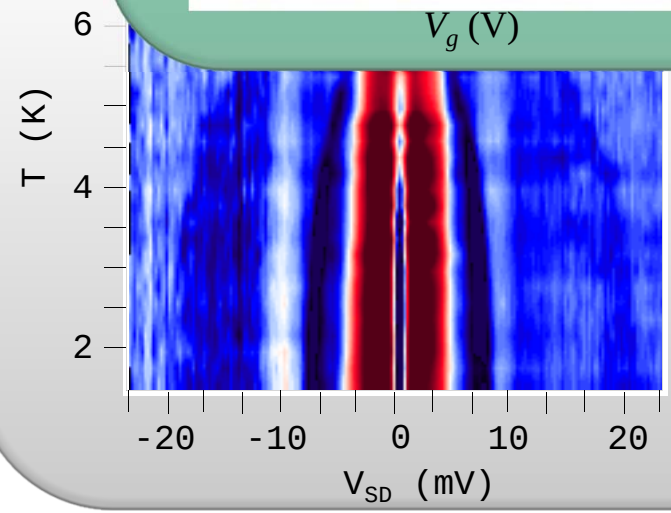


Potential Interplay between Superconducting System and QHE



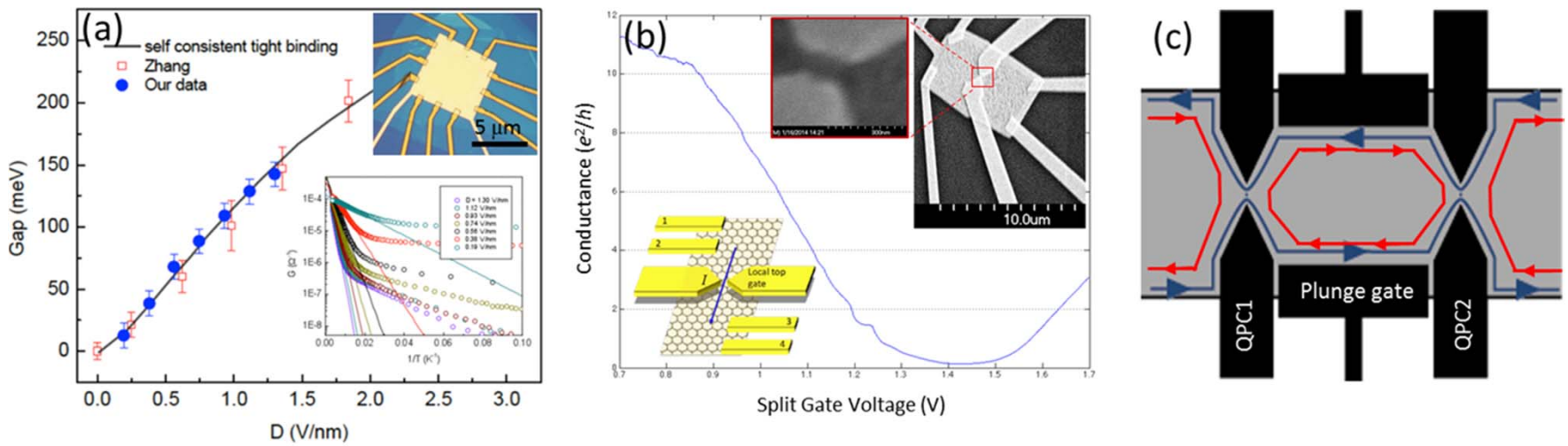
Andreev Reflection



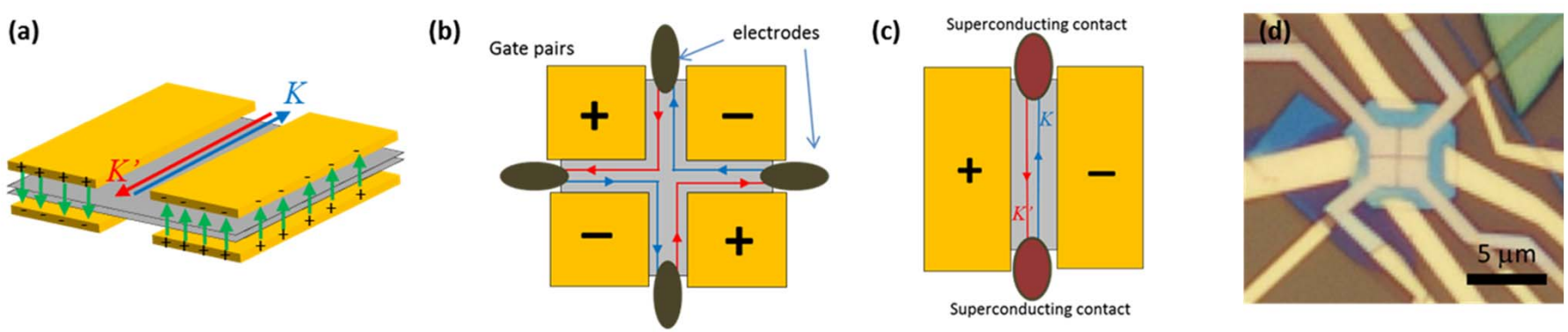


Outlook I: graphene mesoscopic physics

Quantum point contact, Quantum Hall Interferometers

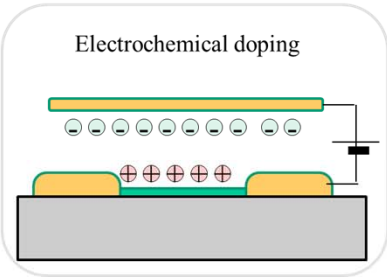


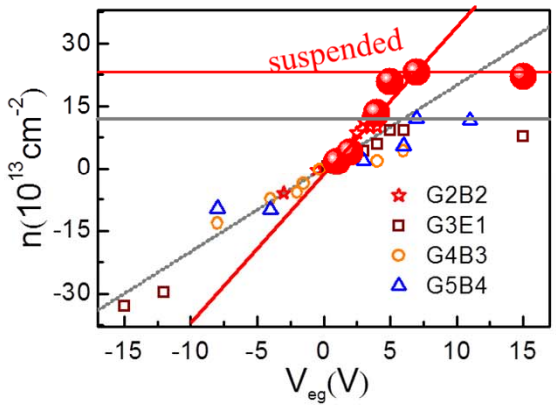
Valleytronics using symmetry protected topological 1-dimensional



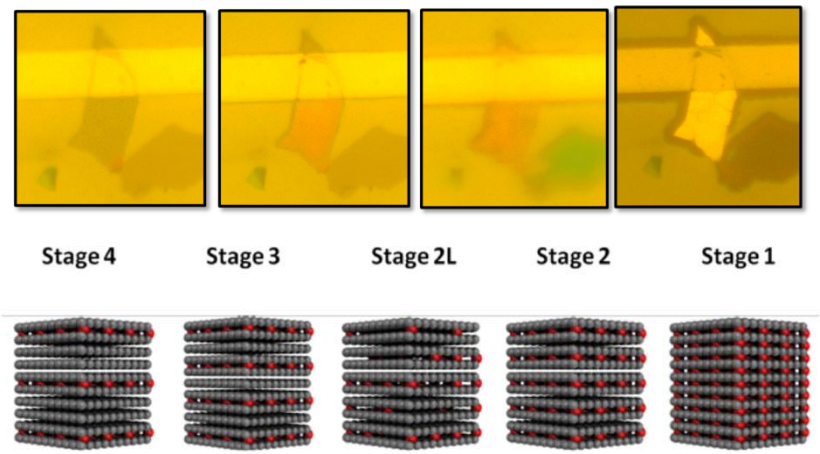
Outlook II: Modification and Growth

Electrochemical doping & intercalation





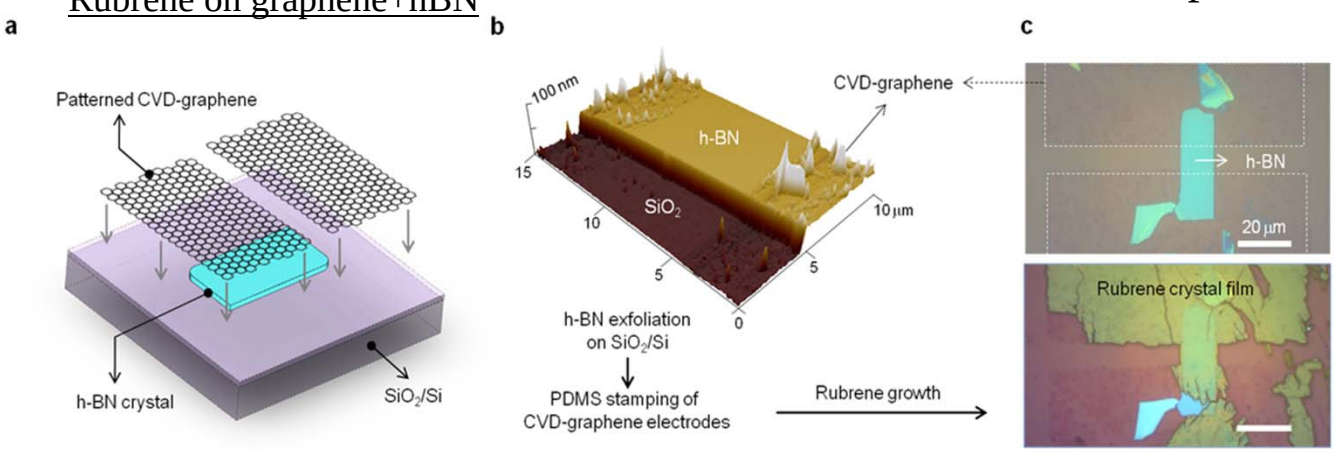
Electrochemical intercalation of ions



Van der Waals Epitaxy Growth

hBN: substrate / tunneling barrier
Graphene: vdW electrodes

Rubrene on graphene+hBN



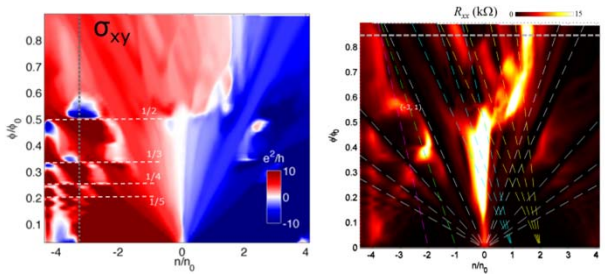
Lee *et al.* (2014)

Summary

- **Graphene/ hBN heterostructures:**

  Observation of Hofstadter's Butterfly

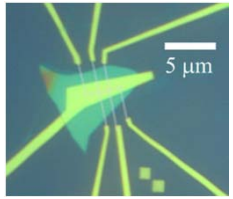
  Dean *et al*, *Nature* (2013);
  similar results were reported by Gorbachev *et al. Nature* (2013)
  and Hunt *et al. Science* (2013)

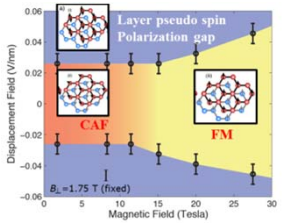


- **Bilayer graphene:**

  e-e interaction and spin and pseudo-spin SU(4) phase space

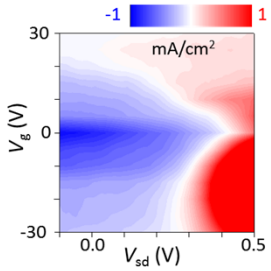
  Maher *et al*, *Nature Phys.* (2013);
  similar results were reported by Hunt *et al. Science* (2013)

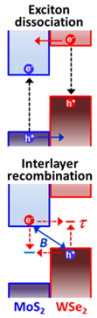




- **Van der Waals Heterostructures:**

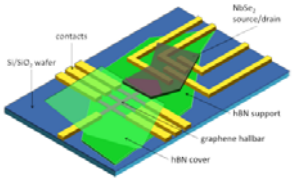
  Gate tunable various van der Waals vertical planar junctions

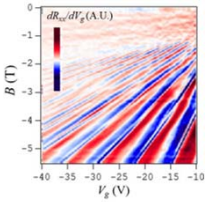




- **$NbSe_2$/graphene:**

  Andreev reflection and interplay between superconducting and QHE





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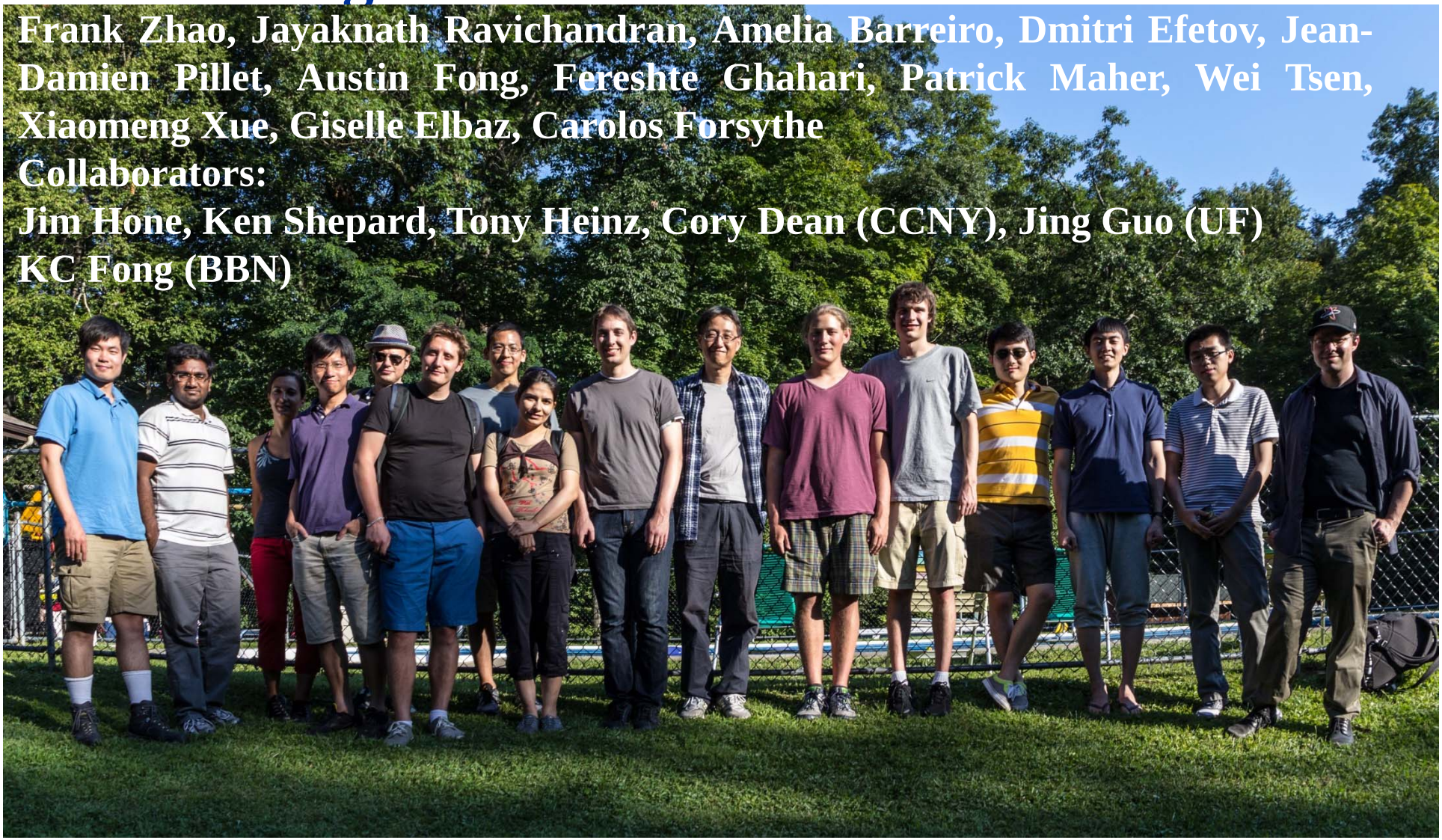

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