2D Materials

an introduction starting from the discovery of graphene

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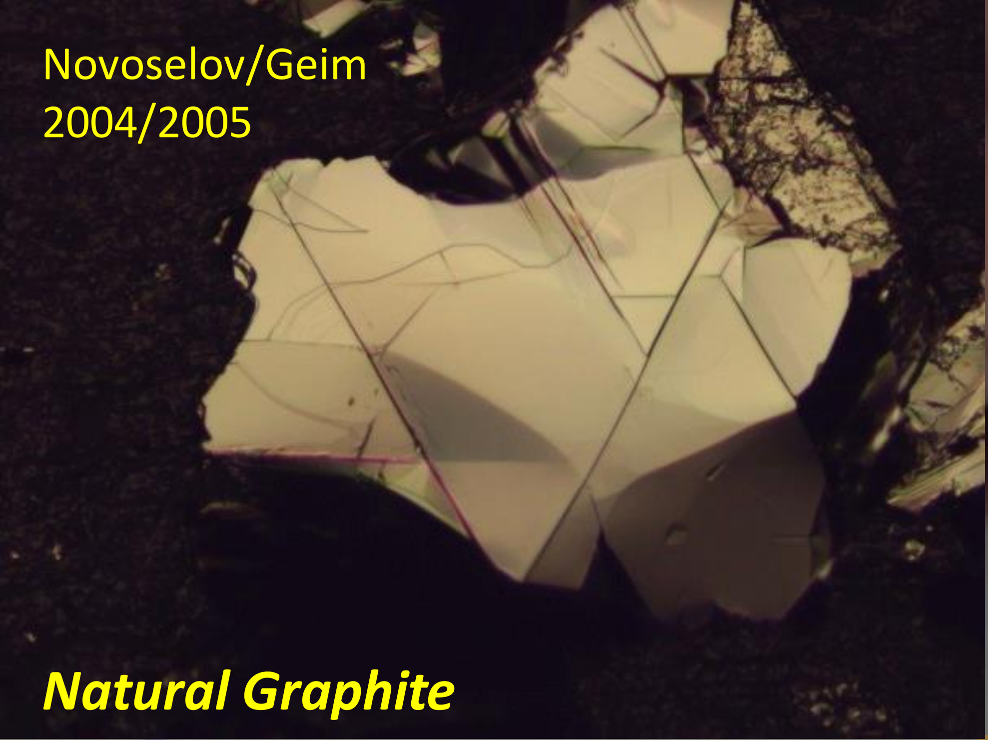
- Developments in material control now enable *perfect crystals only one or a few atom thick to be investigated*

- The very broad variety of 2D materials available gives *access to unexplored physical phenomena*

- *Realization of artificial materials* with properties engineered by design at the atomic scale

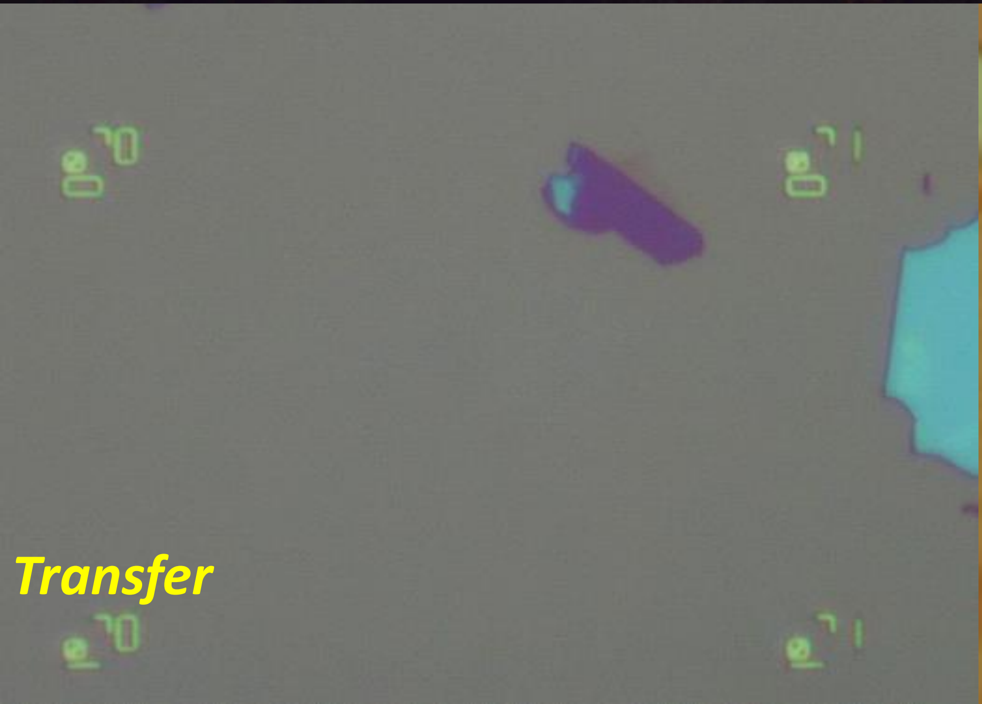
Philosophy: some idea is better than no idea



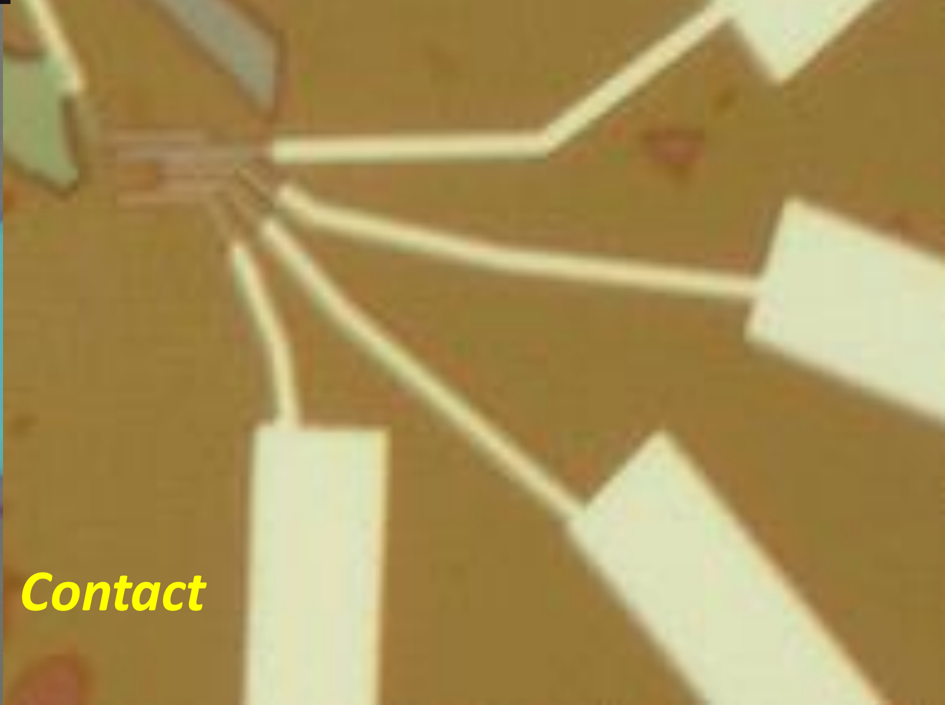
Novoselov/Geim
2004/2005

Natural Graphite

Exfoliation

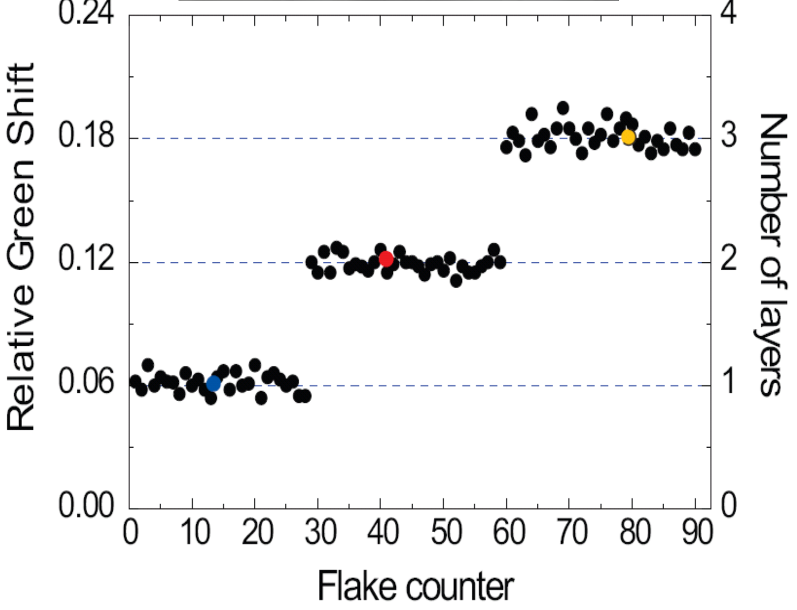


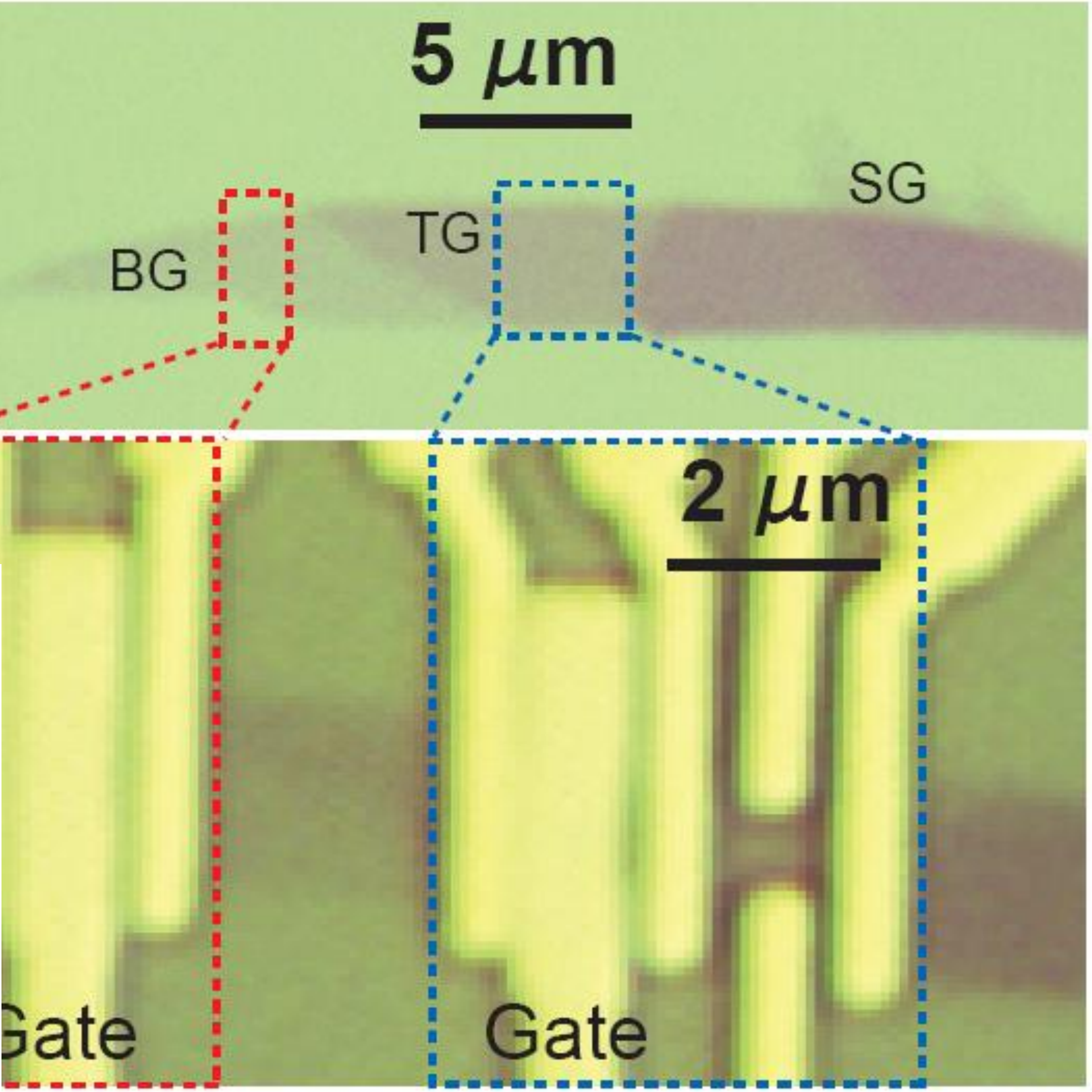
Transfer



Contact

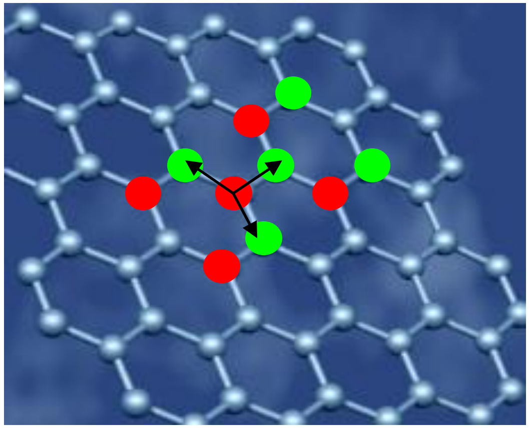
Seeing one-atom layers one at a time





Relativistic electrons in graphene

Two inequivalent C atoms



$$H = t\sum_{i,j} A^{\dagger}_{\vec{R}_i} B_{\vec{R}_i+\vec{\delta}_j} + B^{\dagger}_{\vec{R}_i+\vec{\delta}} A_{\vec{R}_i}$$

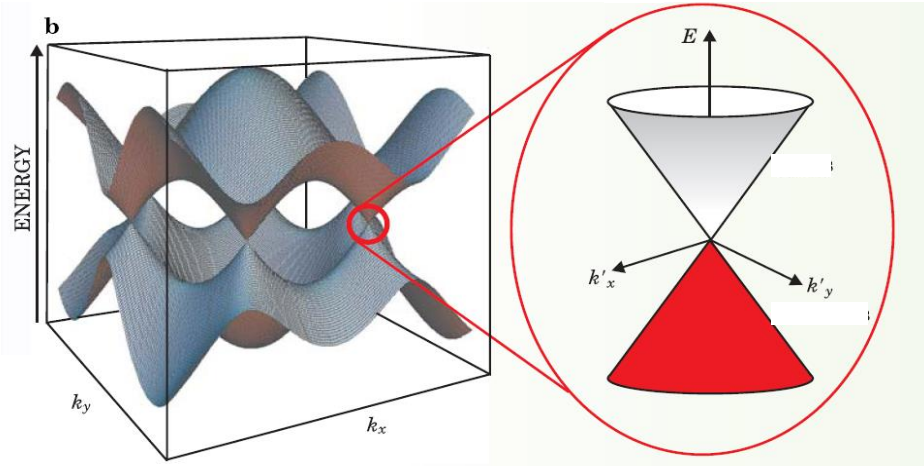
$$|\psi_k >= \left(\alpha_k \sum_i \left(e^{i\vec{k}\vec{R}_i} A^{\dagger}_{\vec{R}_i} \right) + \beta_k \sum_i \left(e^{i\vec{k}\vec{R}_i} B^{\dagger}_{\vec{R}_j} \right) \right) |0>$$

Or

$$|\psi_k >= \sum_i e^{i\vec{k}\vec{R}_i} \begin{pmatrix} \alpha_k A^{\dagger}_{\vec{R}_i} \\ \beta_k B^{\dagger}_{\vec{R}_j} \end{pmatrix} |0>$$

pseudo spin

$H\,|\psi_k\rangle = E(k)\,|\psi_k\rangle$



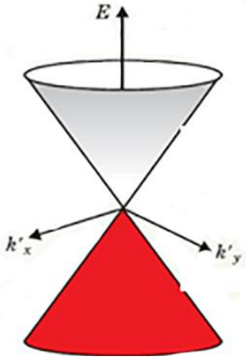
Dirac Equation

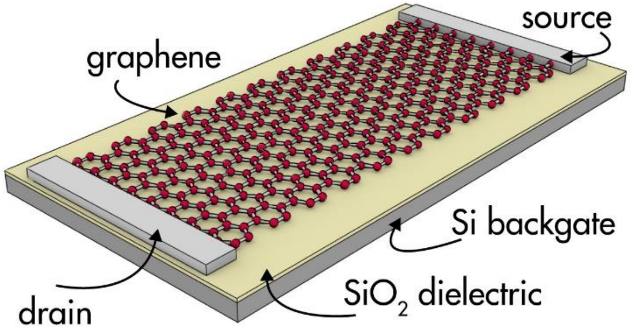
$$v_F(-i\hbar\vec{\nabla})\cdot\vec{\sigma}\begin{pmatrix} \alpha_k e^{i\vec{k}\cdot\vec{r}} \\ \beta_k e^{i\vec{k}\cdot\vec{r}} \end{pmatrix} = E(k)\begin{pmatrix} \alpha_k e^{i\vec{k}\cdot\vec{r}} \\ \beta_k e^{i\vec{k}\cdot\vec{r}} \end{pmatrix}$$

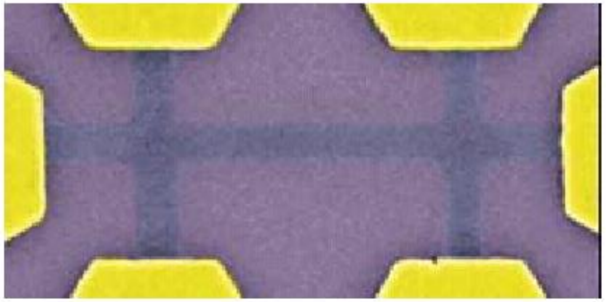
Direct Experimental manifestations

Graphene field-effect transistor

Novoselov/Geim/Kim2005

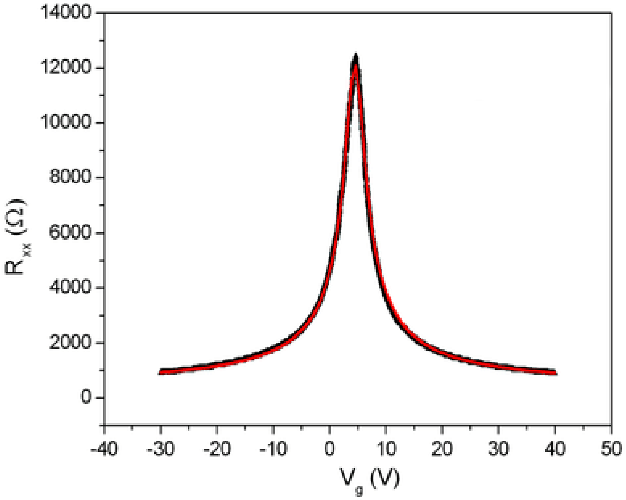


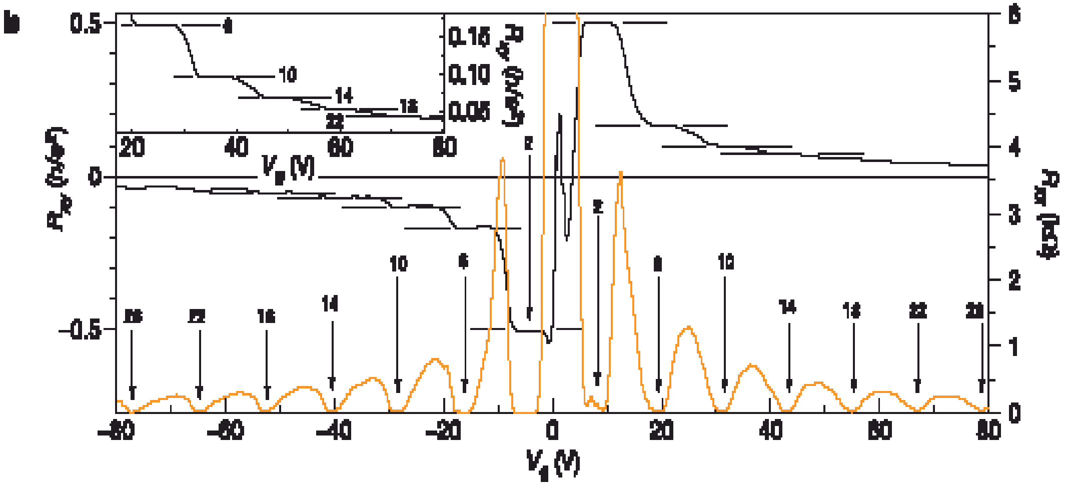




Resistivity

Quantum Hall effect



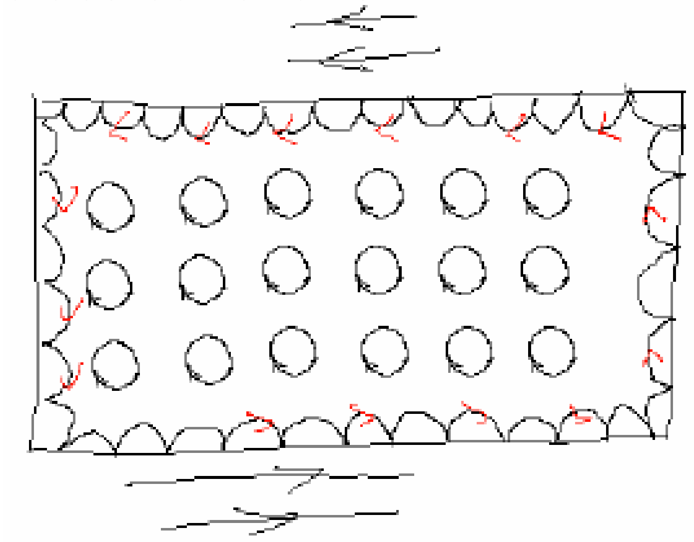


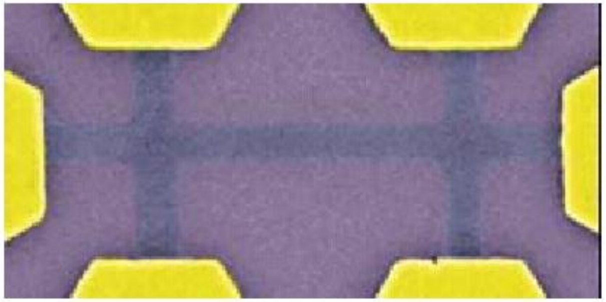
Dirac "peak"

$$G_{Hall} = 4\frac{e^2}{h}\left(N + \frac{1}{2}\right)$$

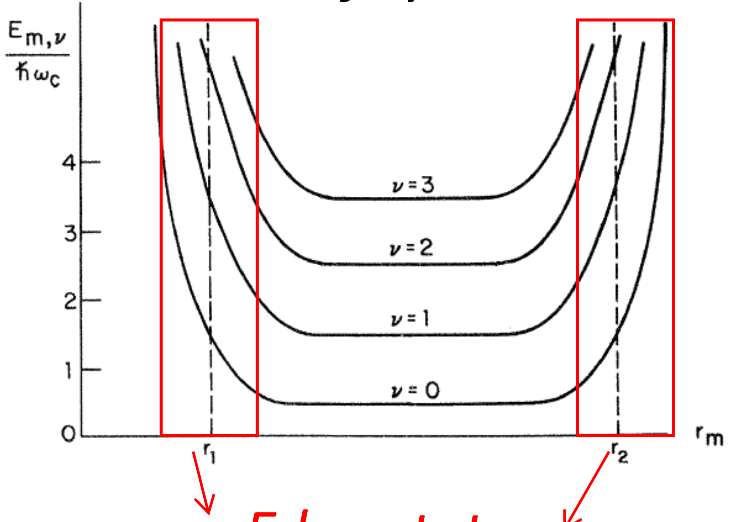
Quantum Hall effect for dummies

Quasiclassical orbits



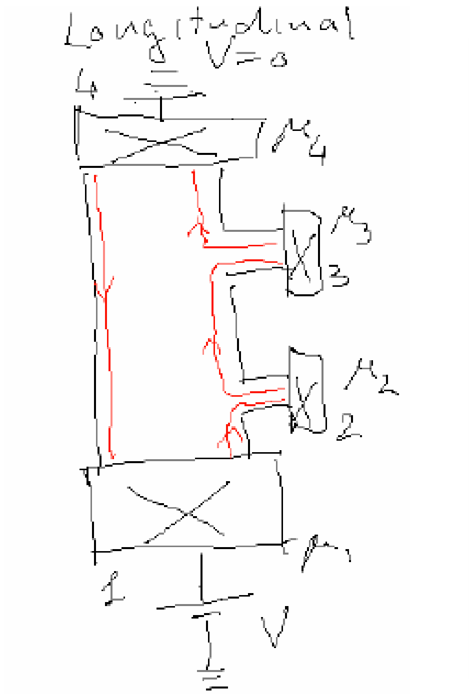


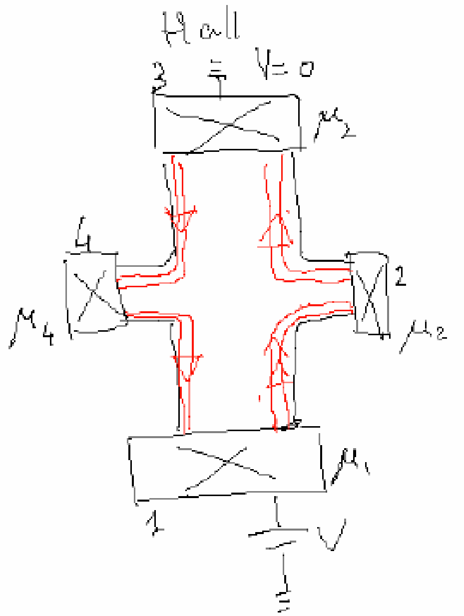
Landau levels =
quantization of cyclotron motion



Edge states

Transport through edge channels





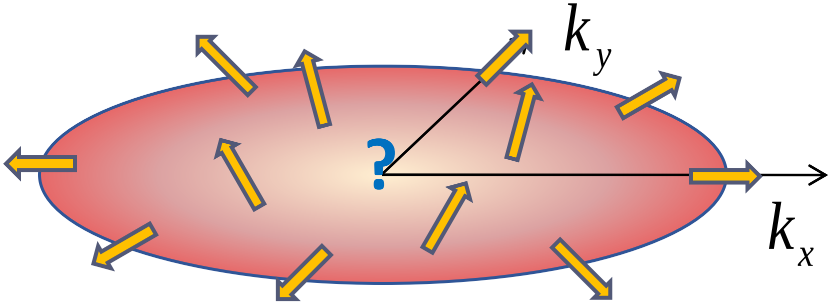
Band structure topology: basic idea

Think of Hamiltonian as a k-dependent magnetic field

Graphene $H = v_F\left(-i\hbar\vec{\nabla}\right)\cdot\vec{\sigma} = \hbar v_F\begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix}$

$$H = \alpha\,\vec{B}\left(\vec{k}\right)\cdot\,\vec{\sigma}$$

$$\vec{B}\left(\vec{k}\right) = \left(k_x, k_y, 0\right)$$



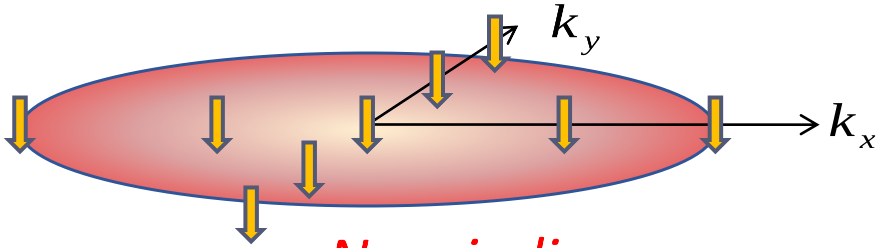
Bloch functions wind around in the Brillouin zone = topologically non-trivial

Trivial insulator

$$H = A\begin{pmatrix} \Delta/2 + bk^2 & 0 \\ 0 & -\frac{\Delta}{2} - bk^2 \end{pmatrix} =$$

$$= A\,B_z\sigma_z$$

$$\vec{B}\left(\vec{k}\right) = \left(0,0,\Delta/2 + bk^2\right)$$

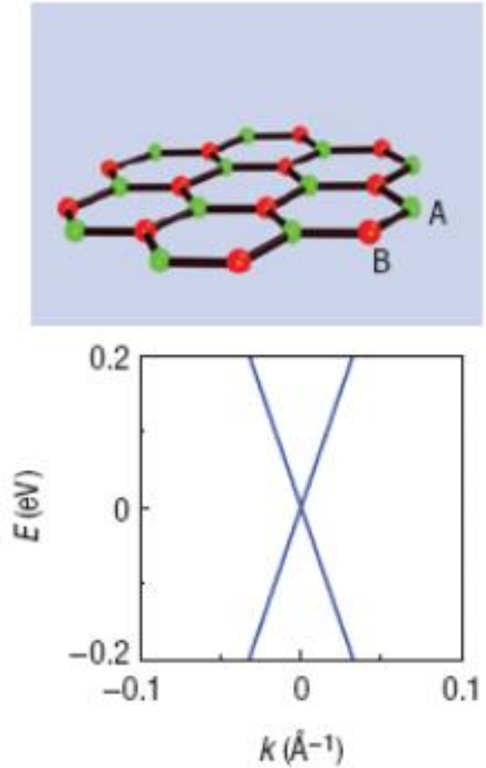


No winding

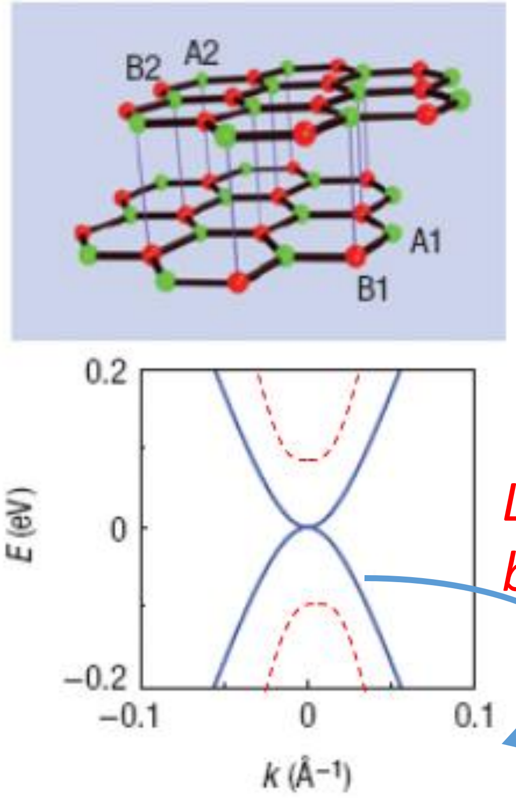
Non-trivial topology leads to states at the edges

Different thickness = different electronic systems

Monolayer



Bilayer



Low-energy band

$$H_{1L} \propto \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix}$$

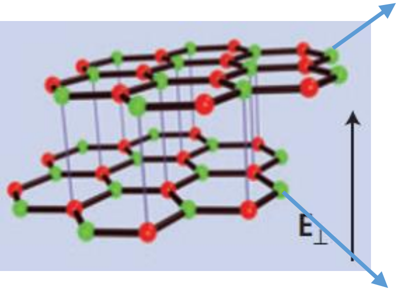
$$H_{2L} \propto \begin{pmatrix} 0 & (k_x - ik_y)^2 \\ (k_x + ik_y)^2 & 0 \end{pmatrix}$$

$$\psi = \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} \qquad E(k) \propto k$$

$$\psi = \begin{pmatrix} \psi_{A1} \\ \psi_{B2} \end{pmatrix} \qquad E(k) \propto k^2$$

Gate control of electronic bands

Layer potential



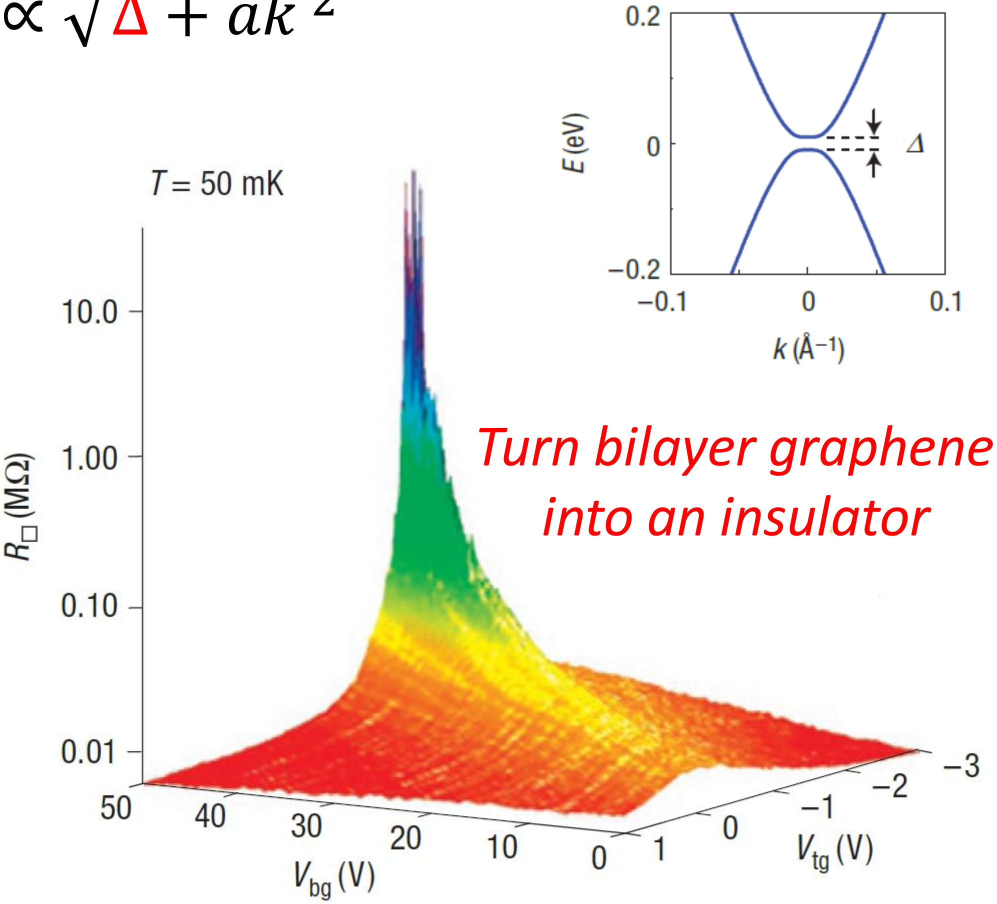
V= Δ/2

V= – Δ/2

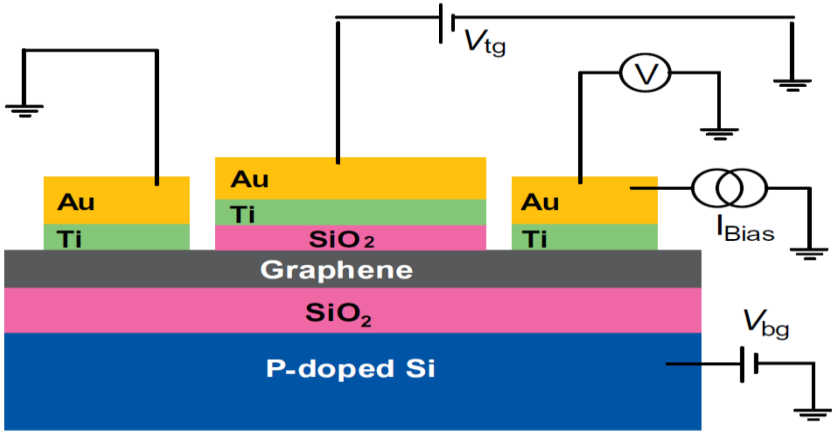
$$H_{2L} \propto \begin{pmatrix} \frac{\Delta}{2} & (k_x - ik_y)^2 \\ (k_x + ik_y)^2 & -\frac{\Delta}{2} \end{pmatrix}$$

$$E(k) \propto \sqrt{\Delta + ak^2}$$

Open band-gap



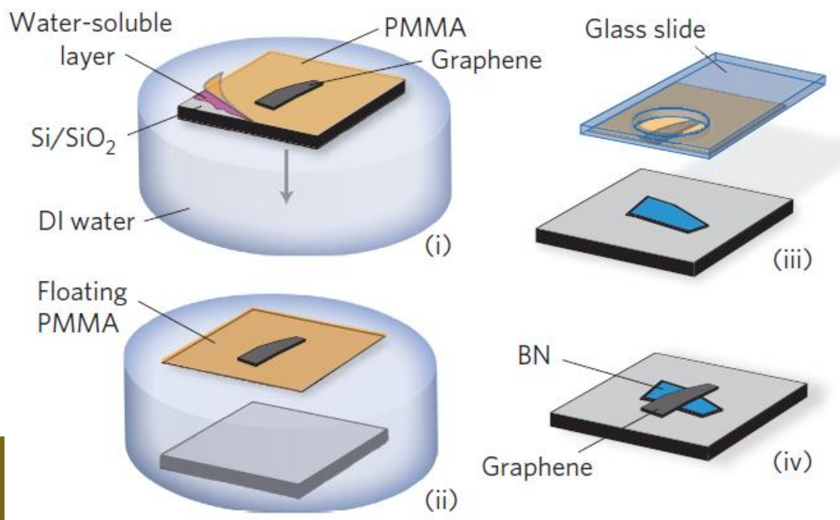
Double-gated devices

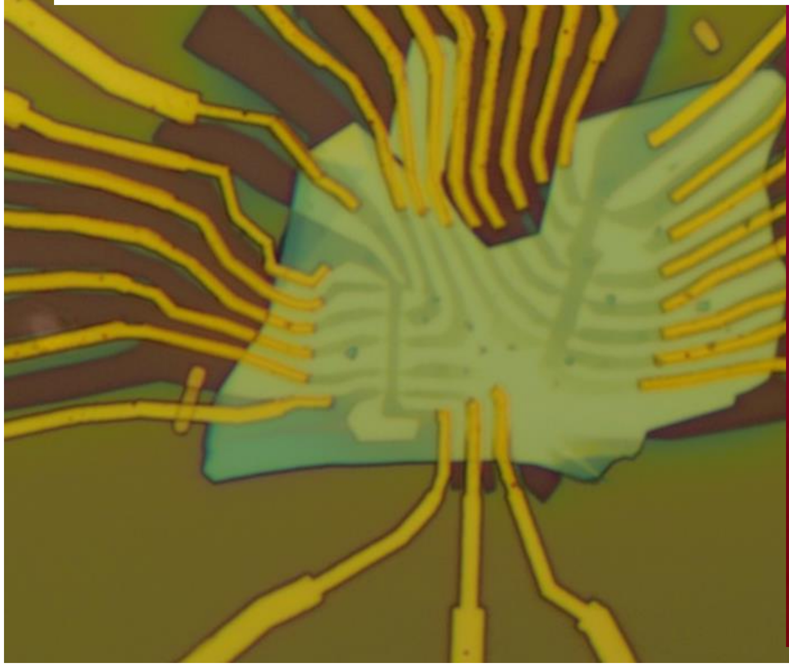


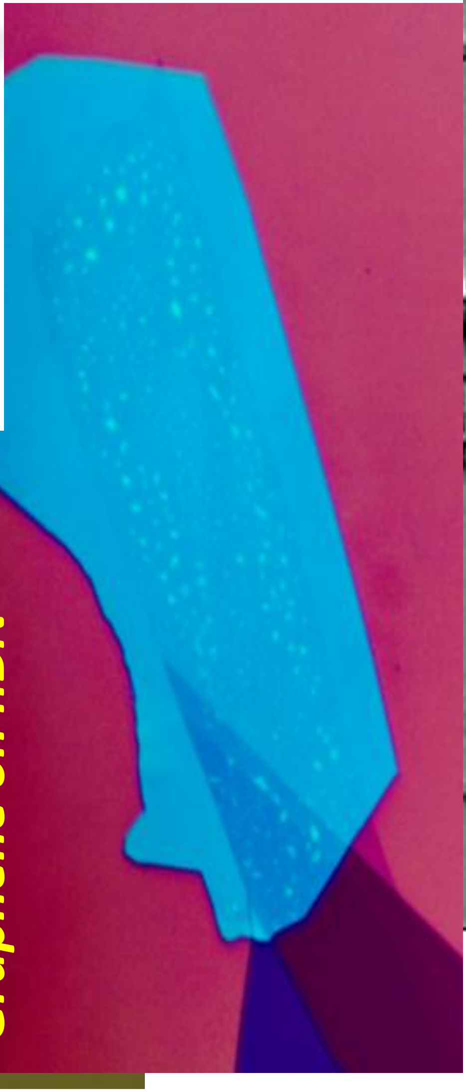
Turn bilayer graphene into an insulator

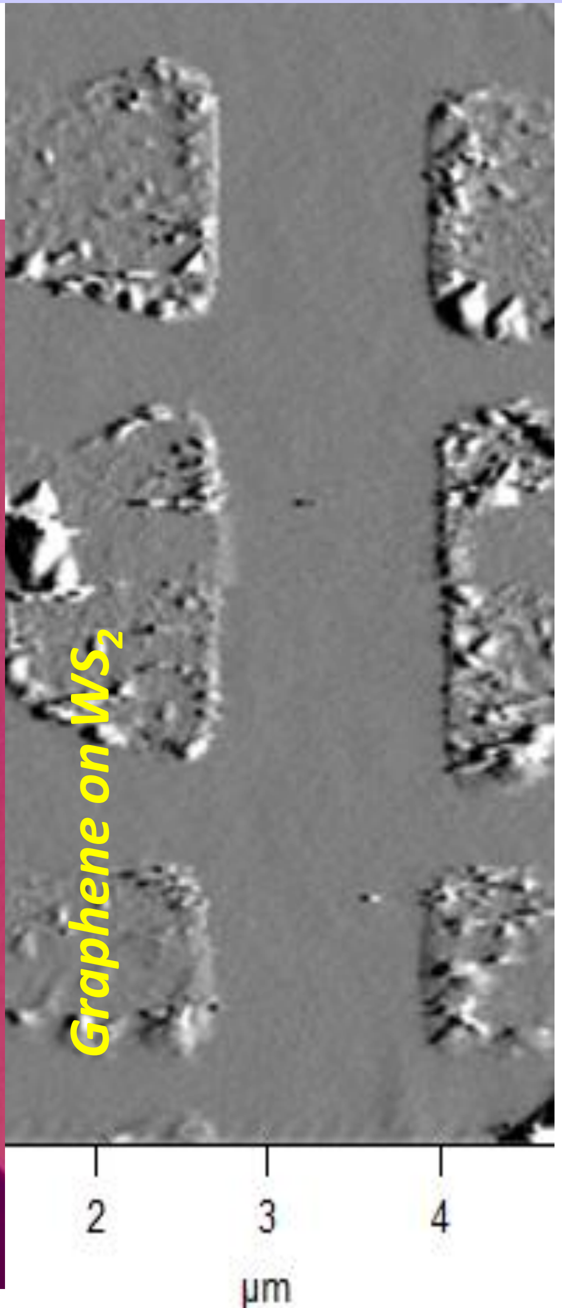
Manipulating atomic crystals

P. Kim's group 2010



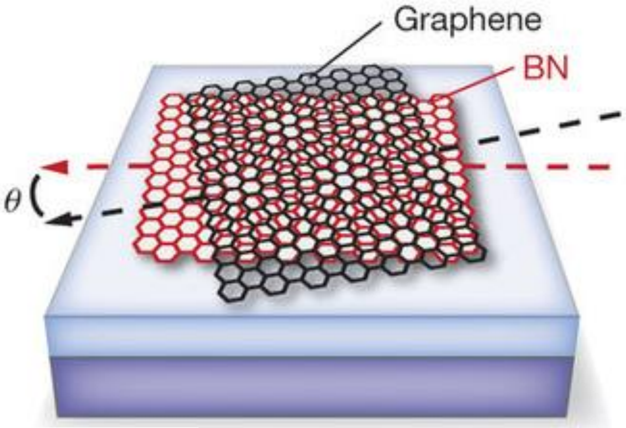


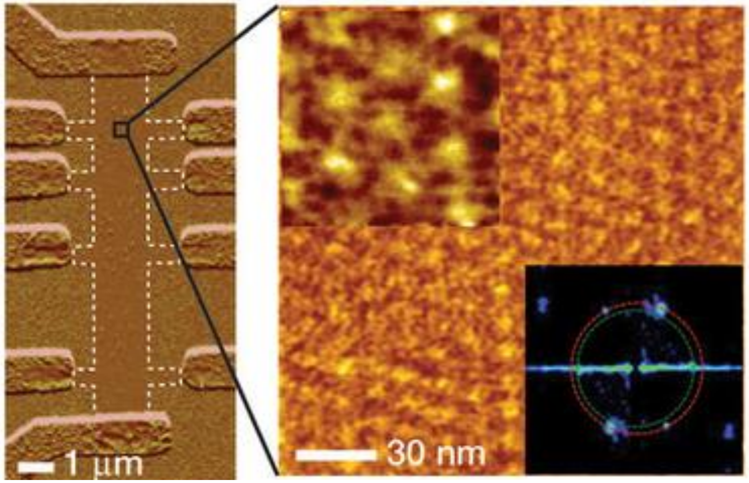


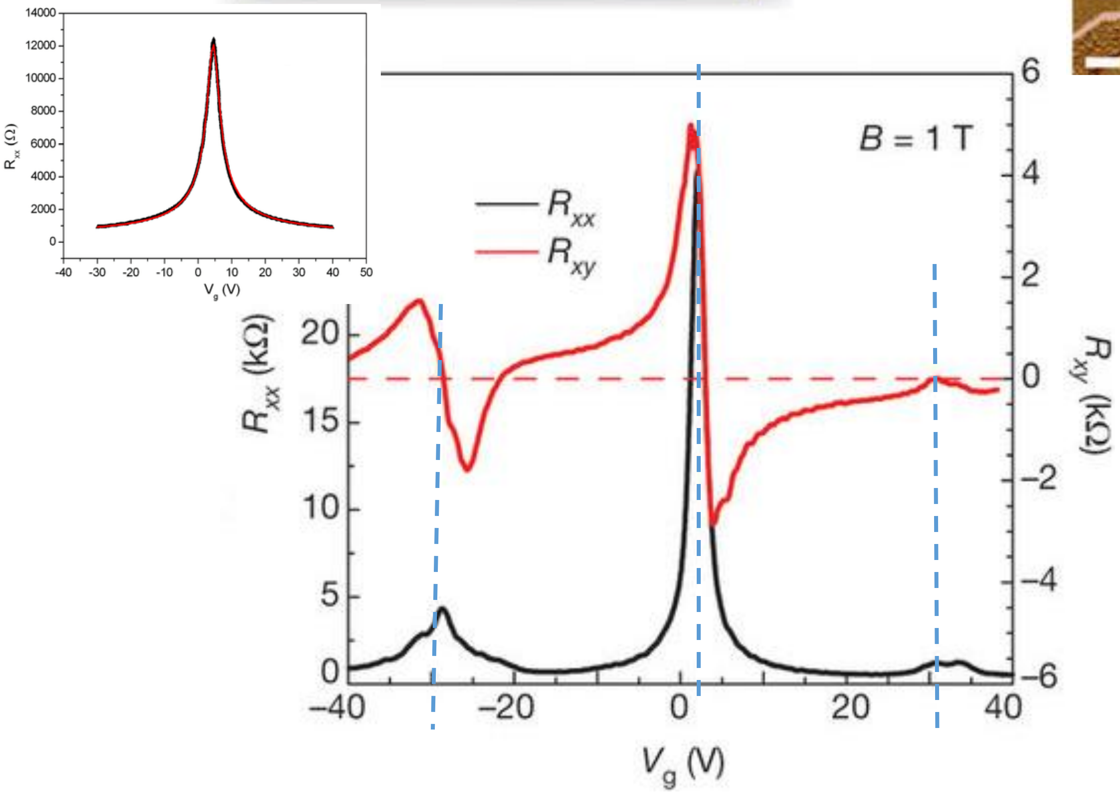


Moire superlattice for graphene on hBN

Kim's group







Satellite Dirac points

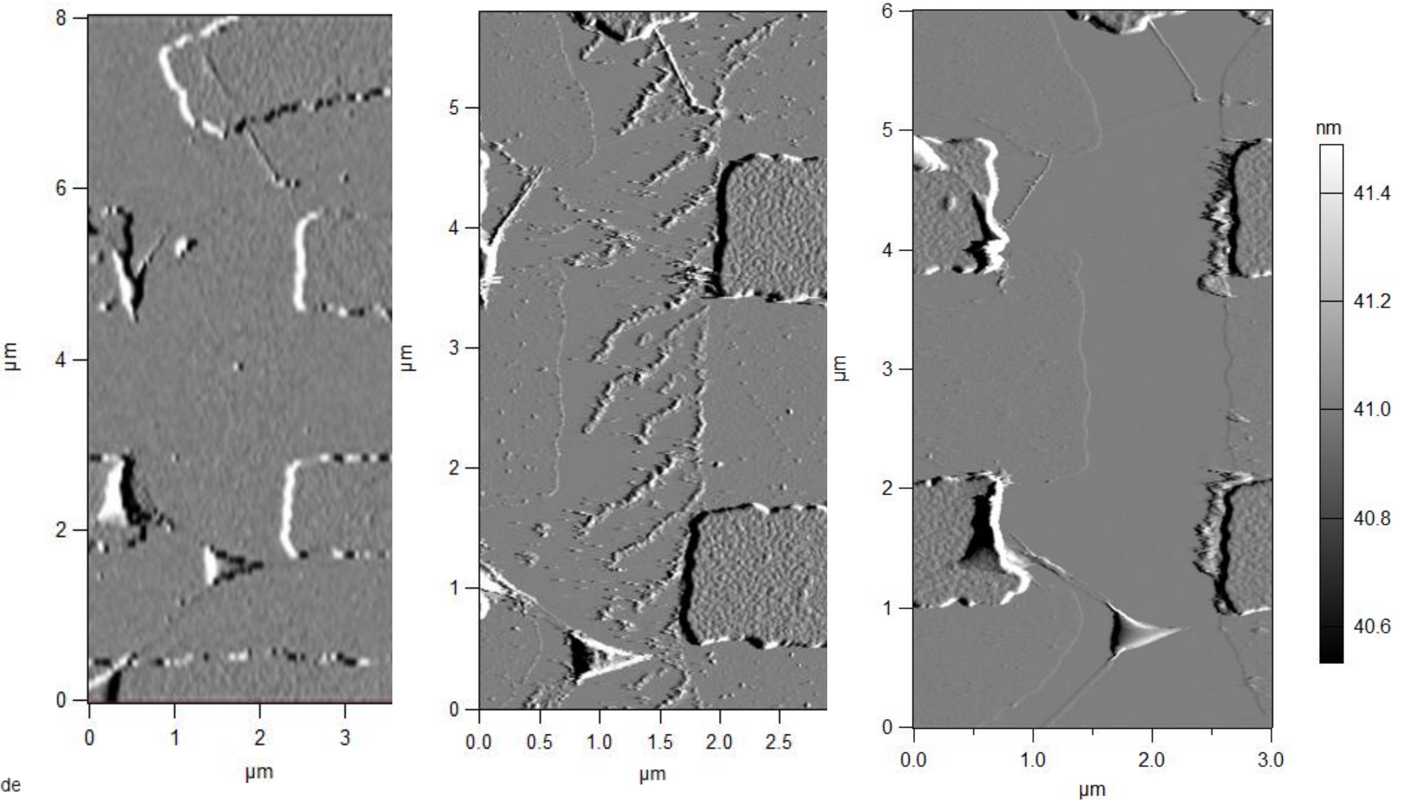
Contact with hBN generates periodic potential:

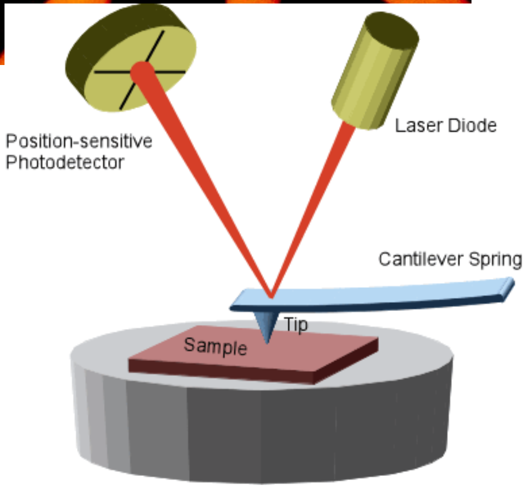
Graphene band structure modified

Cleaning 2D materials

Optical image

Before cleaning → During cleaning → After cleaning

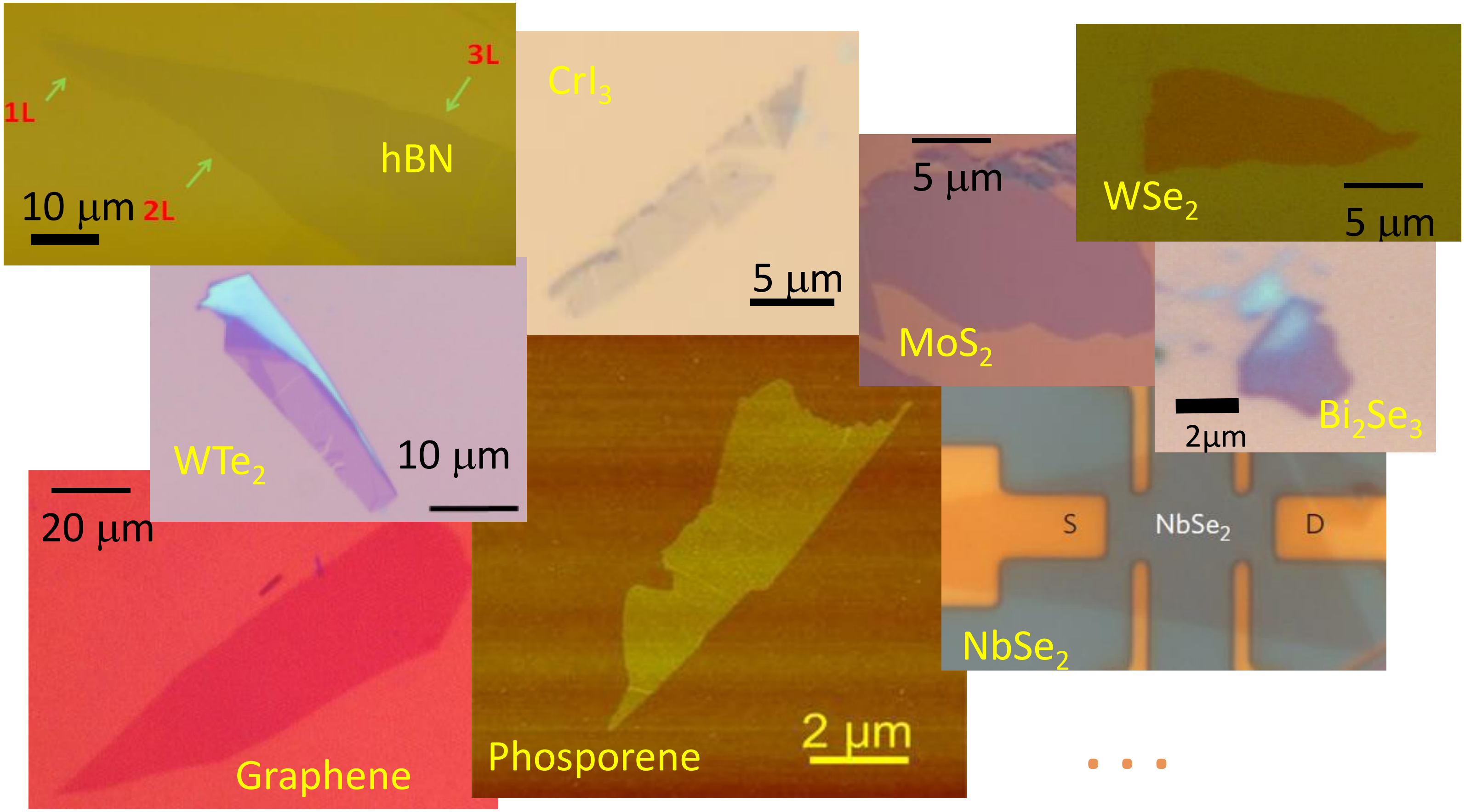




Contact mode AFM removes residues of nano-fabrication processes

A virtually infinite variety of systems

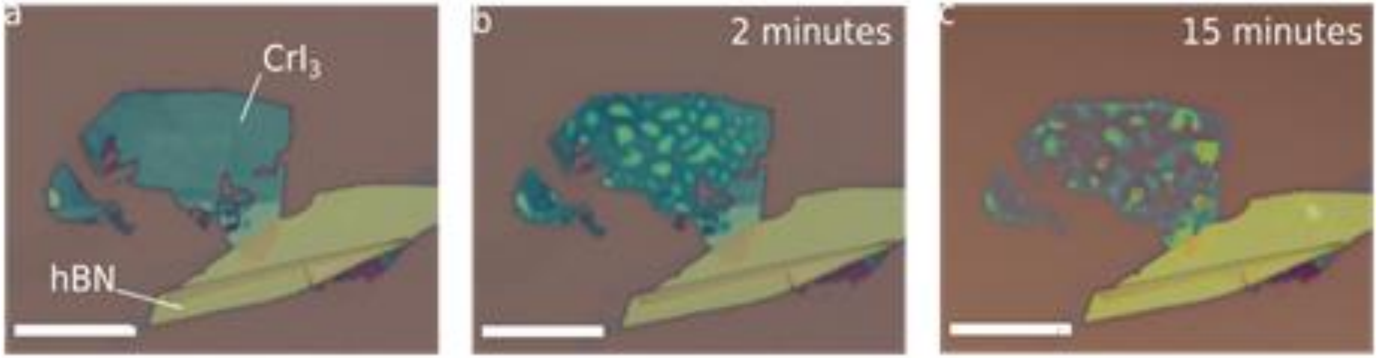
More than 50 monolayers demonstrated, including: Insulators, semiconductors, semi-metals, topological insulators, superconductors, charge density waves, ferromagnets, antiferromagnets…



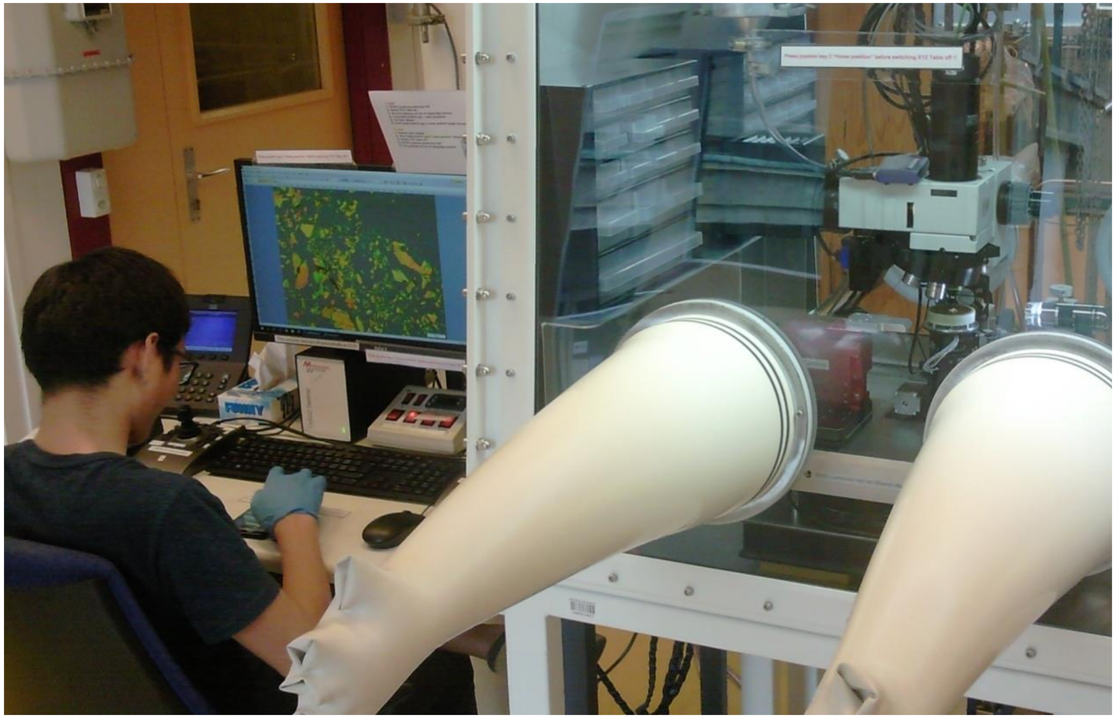
Theory predicts that ~ 1000 different atomic crystals can be produced using similar techniques

Can work with materials not stable in air

Example: CrI_3 --- the first ferromagnetic monolayer



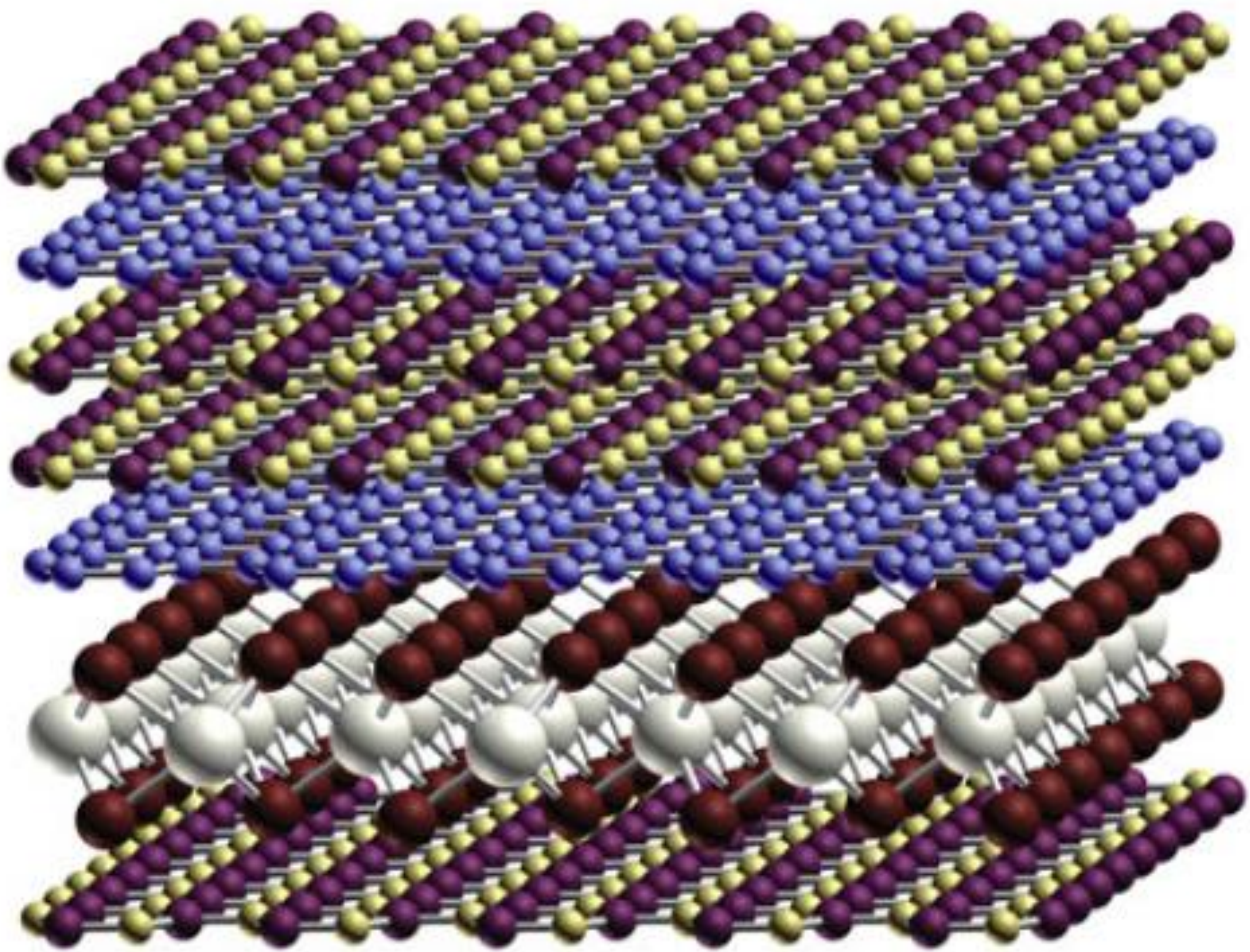
Thin crystals (even 50 nm) dissolve in a few minutes



Exfoliate/transfer/encapsulate in glove box with controlled atmosphere

The Grand Vision – already becoming reality

Novoselov 2011



Examples of interesting physics in 2D materials

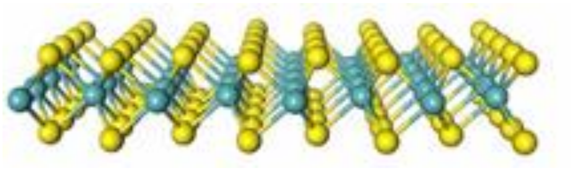
Goal: to illustrate the breadth of scope --- no details

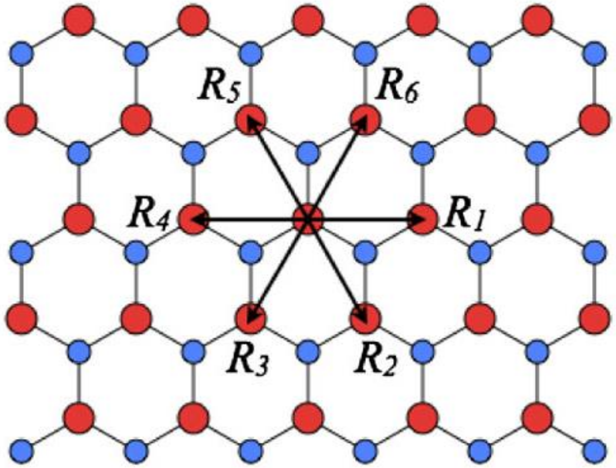
- *Gate-induced superconductivity* in semiconducting transition metal dichalcogenides (TMDs)
- *Giant tunneling magnetoresistance* through 2D magnetic semiconductor tunnel barriers
- *Edge conduction* in monolayer WTe_2 (2D topological insulator)

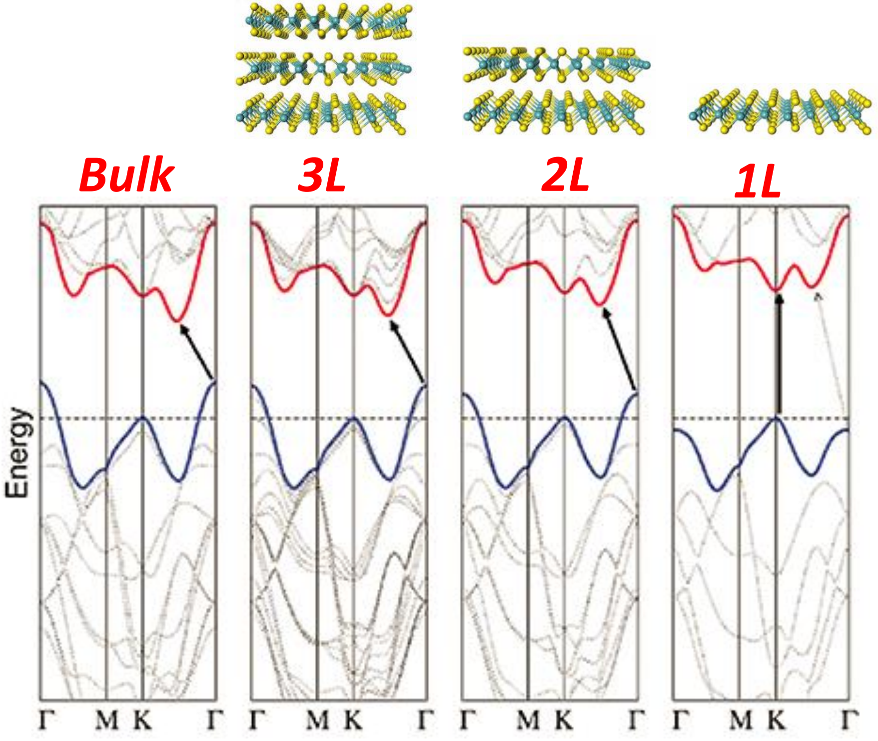
Semiconducting transition metal dichalcogenides

MoS_2, WS_2, $MoSe_2$, WSe_2, …

- *Honeycomb (= graphene),*
- *A/B atom different (=gapped),*
- *very strong SOI*





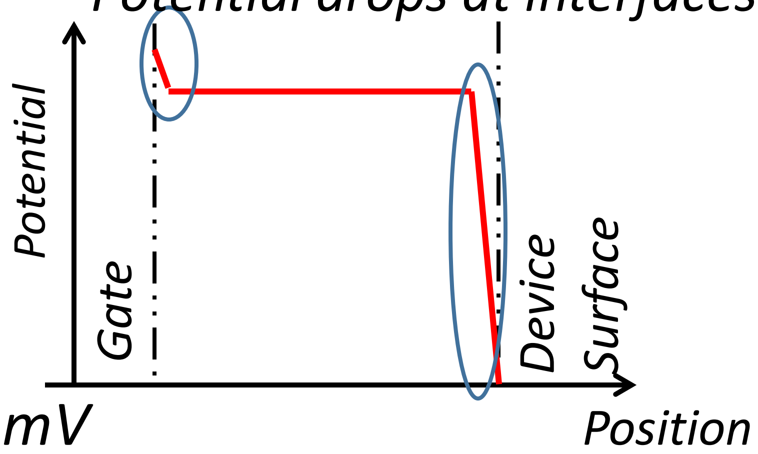


A. Splendiani et al. NL 10, 1271 (2010)

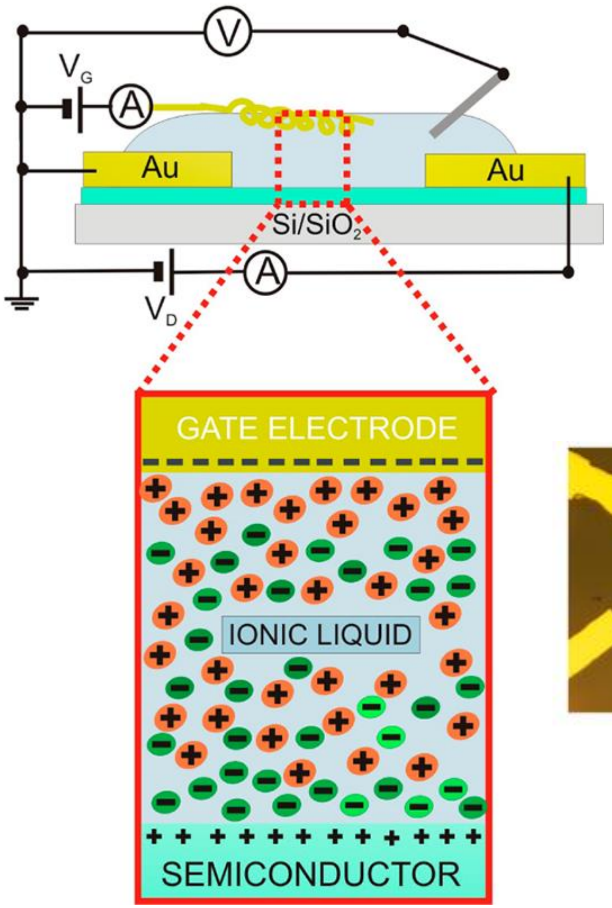
Ionic liquid gating

Electrostatics of ionic liquids
similar to metals =
atomic-scale screening length

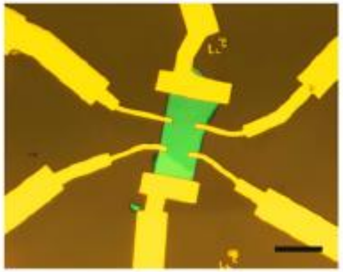
Potential drops at interfaces

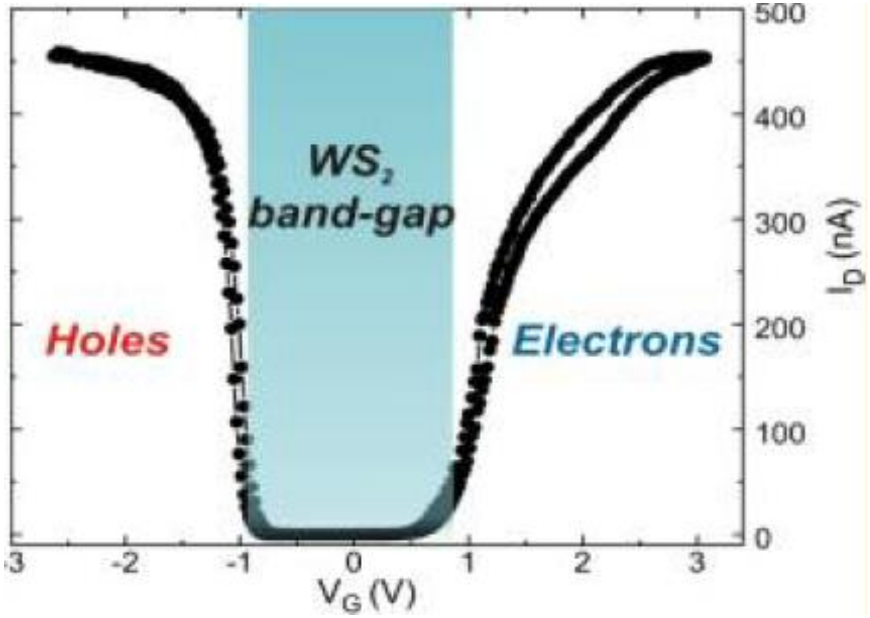


$V_{sd} = 100\ mV$



Ex: WS_2





$$e\Delta V_G = \Delta E_F + e\Delta\phi = \Delta E_F + \frac{e^2 n}{C_G}$$

Gate-induced superconductivity in MoS$_2$ ionic-liquid FETs

Superconducting Dome in a Gate-Tuned Band Insulator

J. T. Ye,[1*] Y. J. Zhang,[1] R. Akashi,[1] M. S. Bahramy,[2] R. Arita,[1,2] Y. Iwasa[1,2*]

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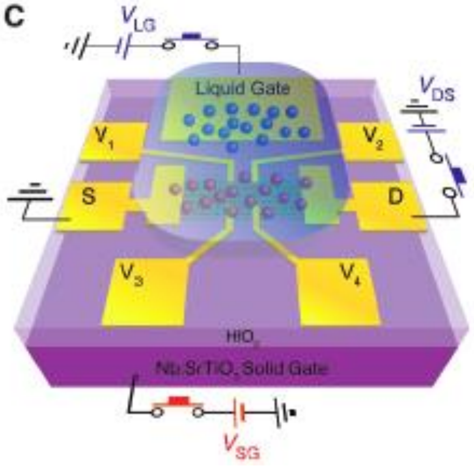
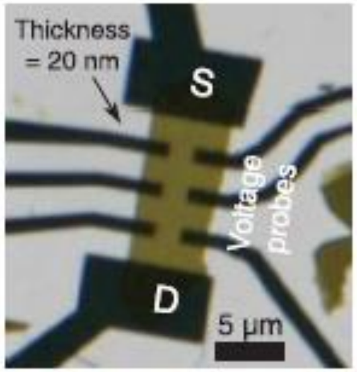
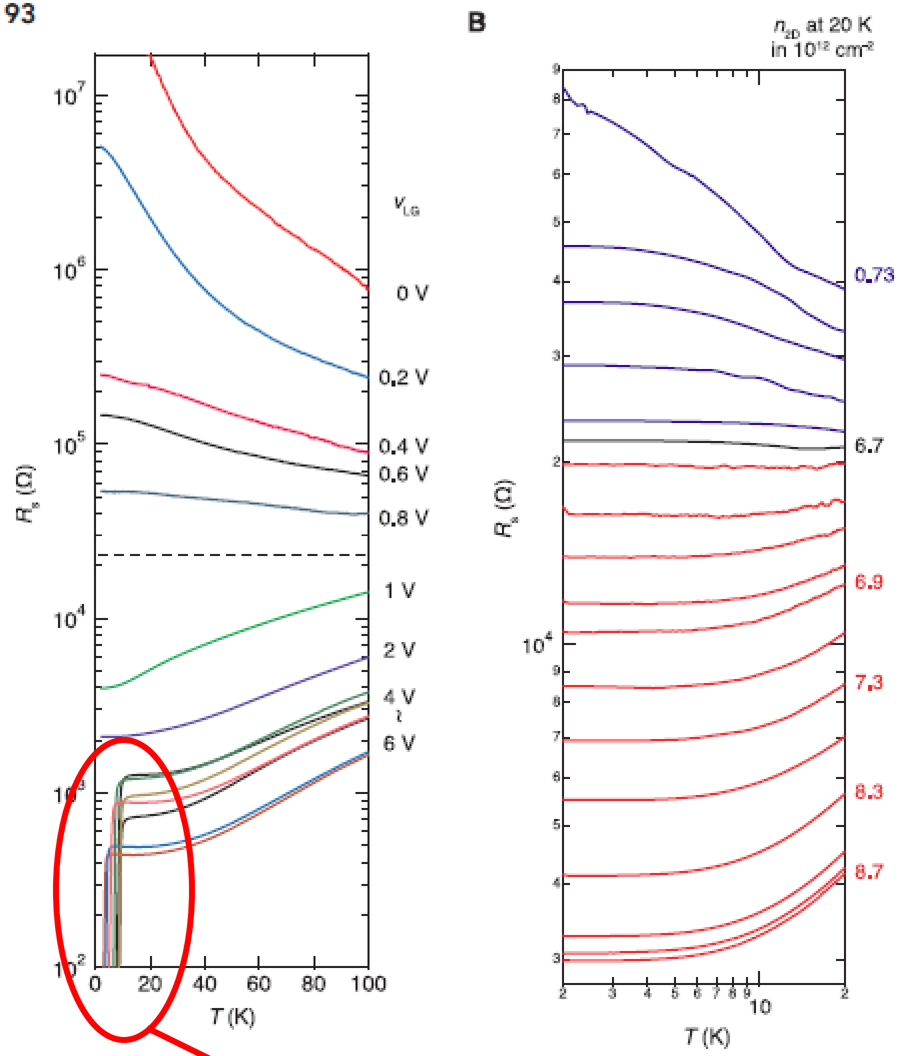




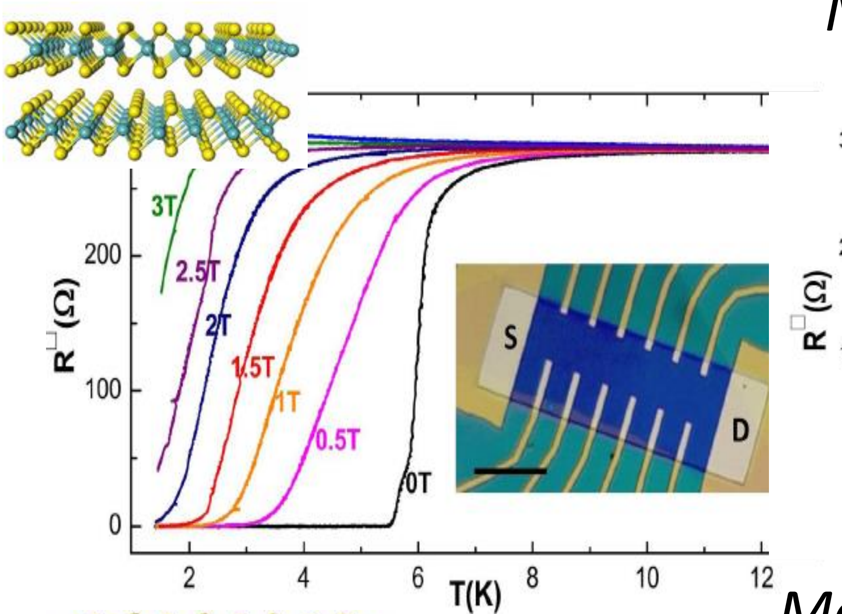
Evolution of the resistance with gate voltage (ionic liquid gate and backgate)

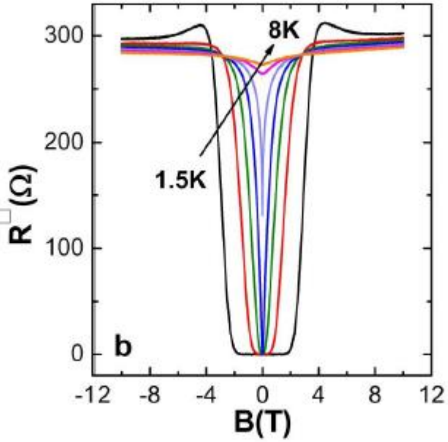


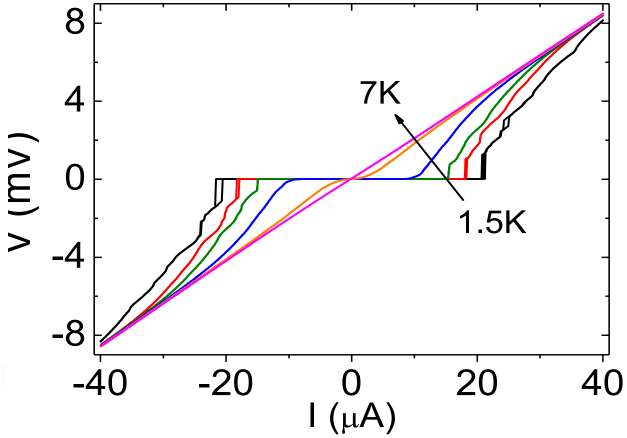
Zero resistance state

Persists in monolayers

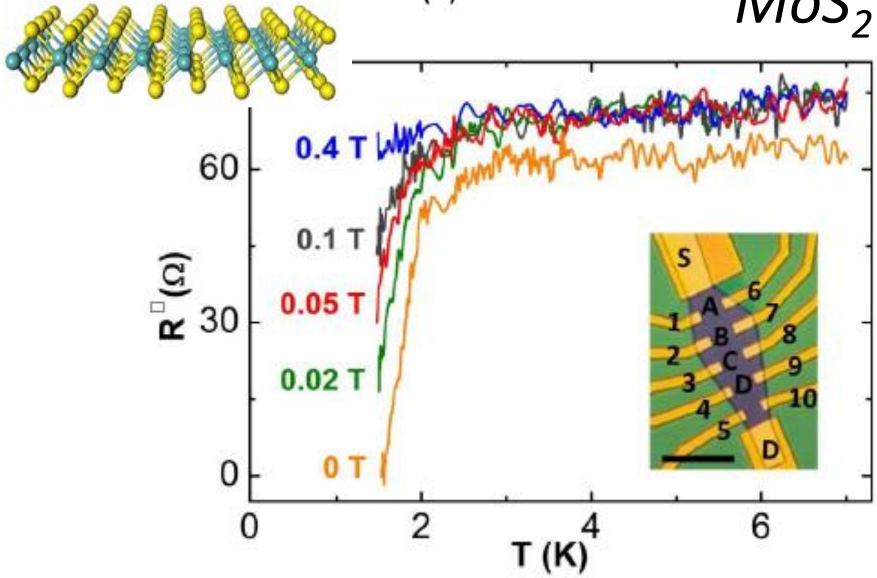
MoS_2 bilayer

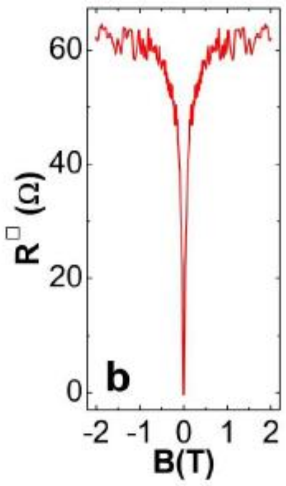






MoS_2 monolayer

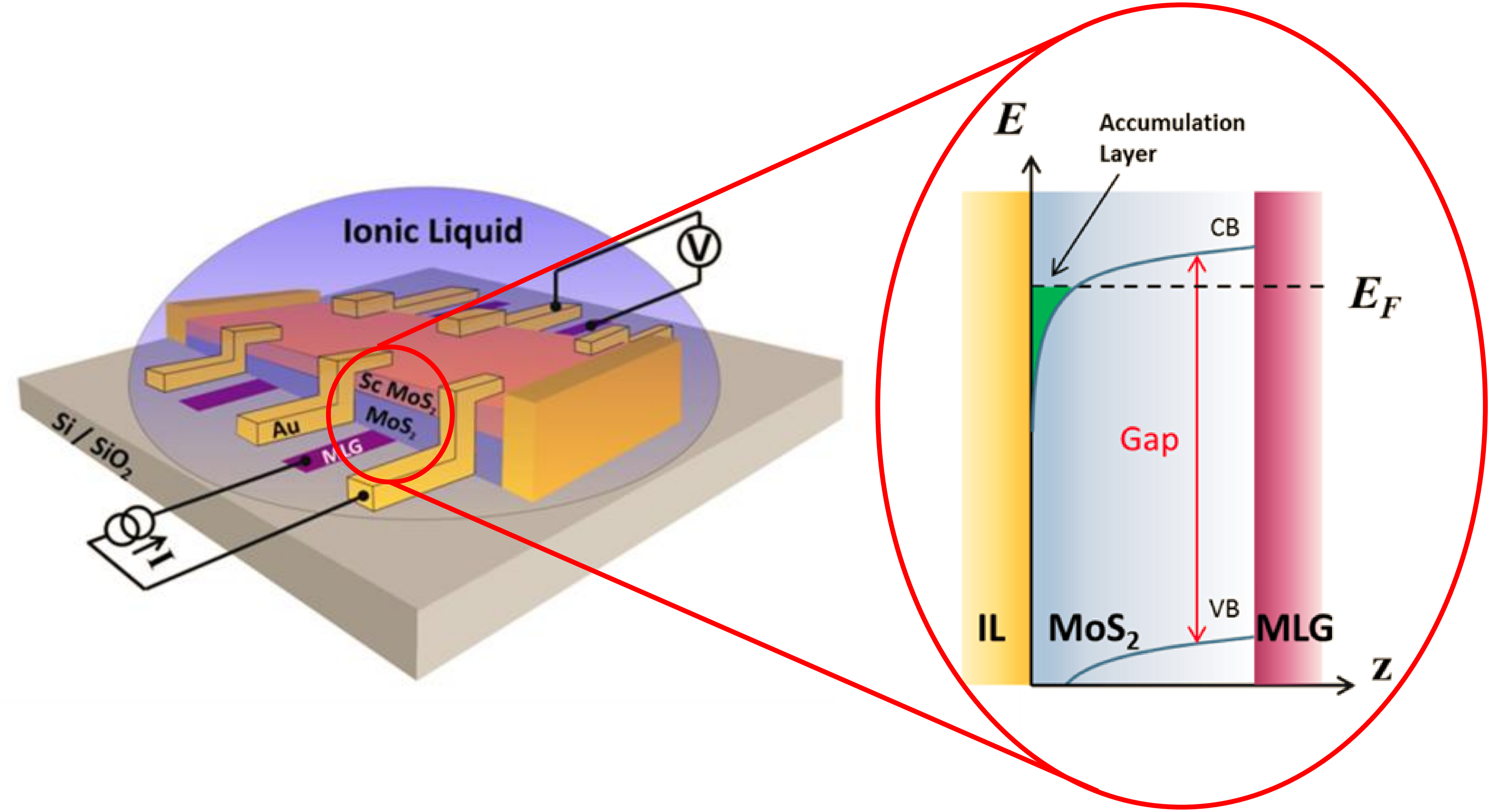




Gate-induced superconductivity in 1L MoS_2 with reduced T_c and H_c

Tunneling spectroscopy

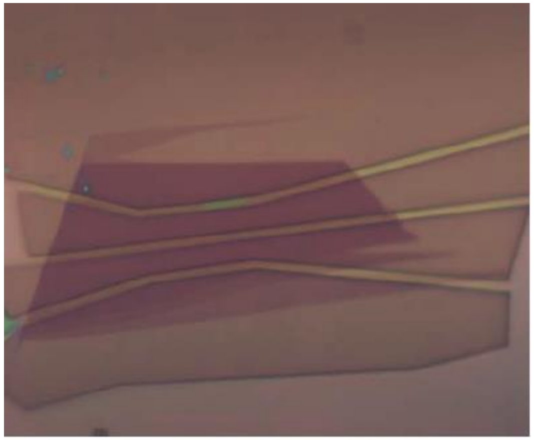
Tunneling into the gate-induced electron accumulation layer



Multilayer graphene as tunneling electrode; MoS_2 as tunnel barrier

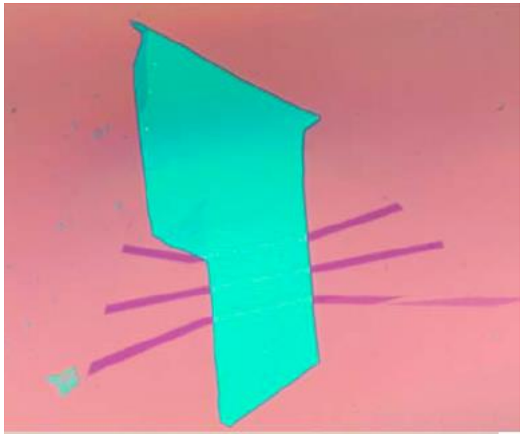
An idea of fabrication steps

Bottom G multilayer

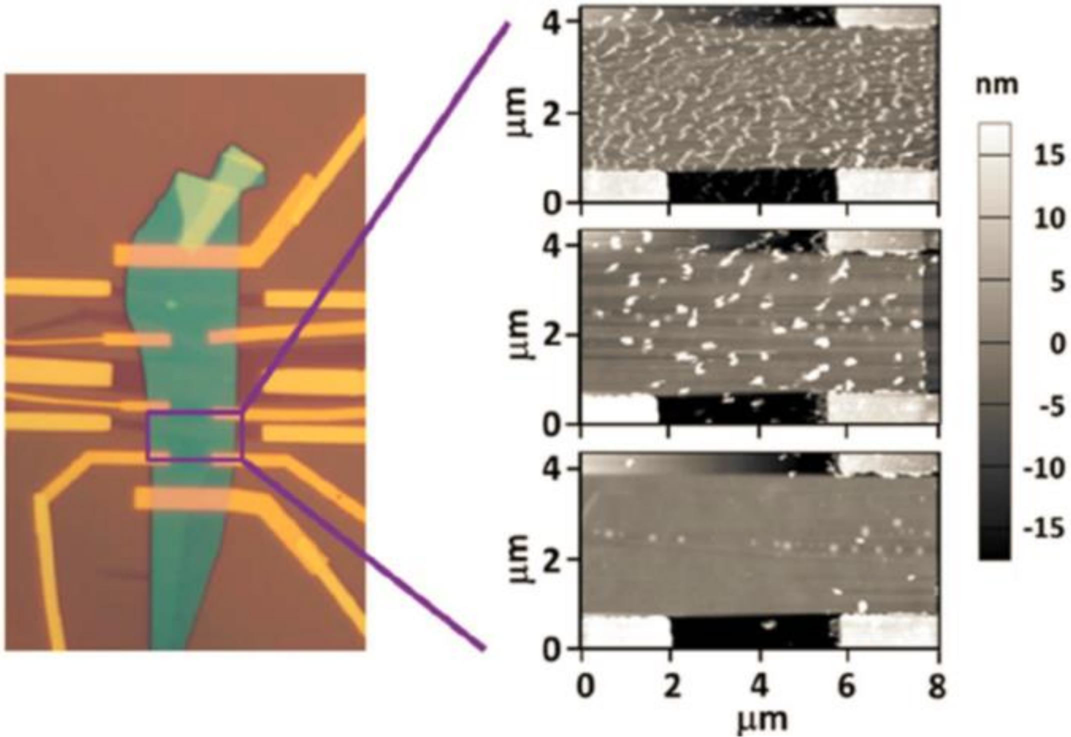


Define tunneling contacts

Transfer MoS_2 multilayer

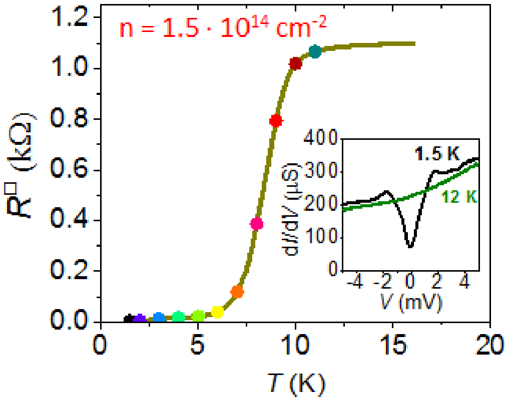


Attach metallic contacts



& clean the MoS_2 surface

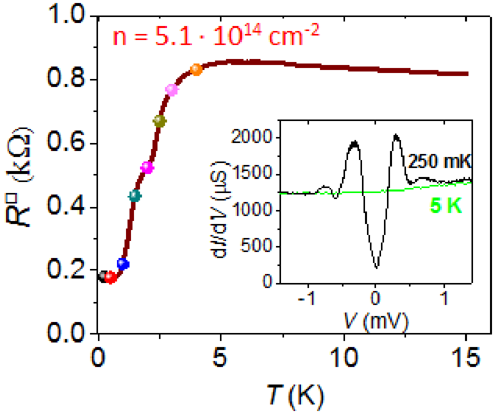
Tunneling spectroscopy of gate-induced superconductivity

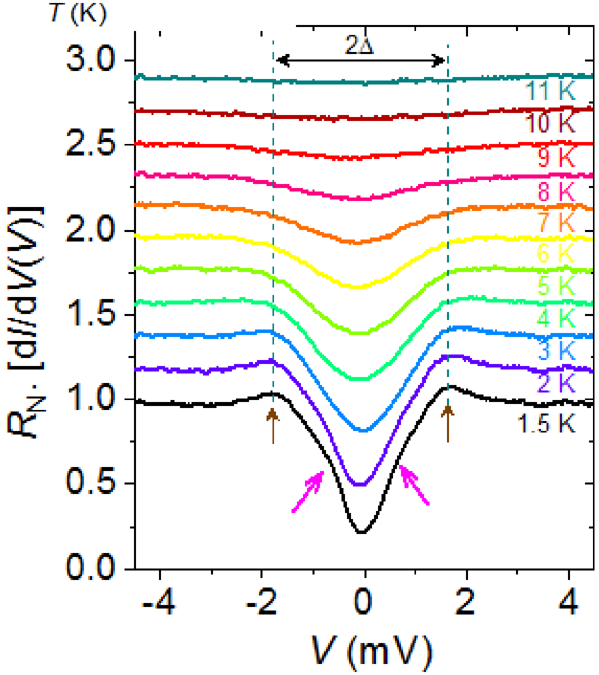


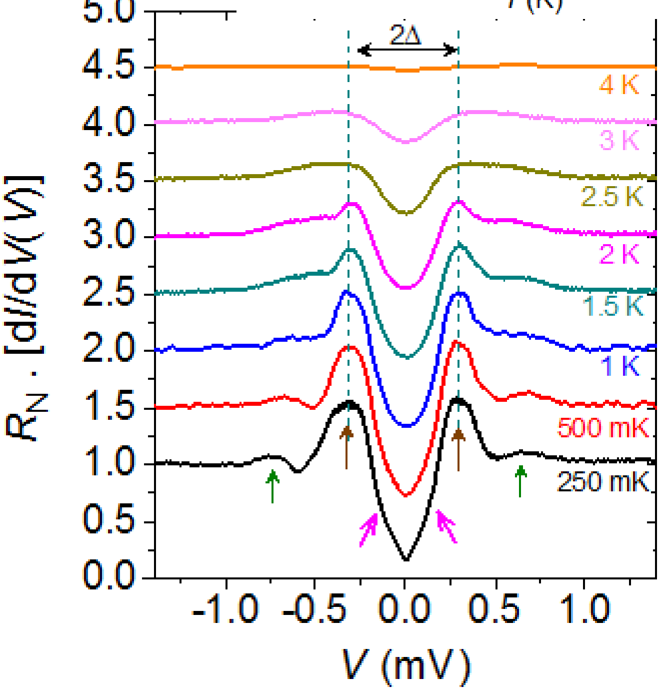
Tunneling spectroscopy

for

10^{14} cm^{-2} < n < 5 10^{14} cm^{-2}





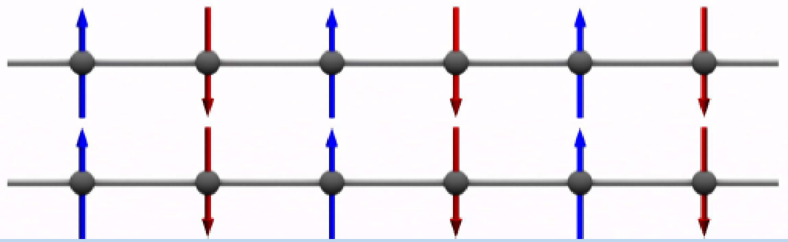
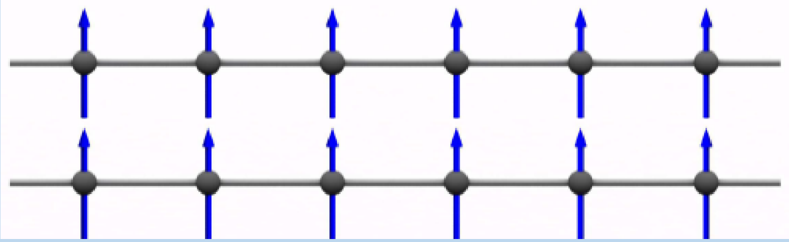
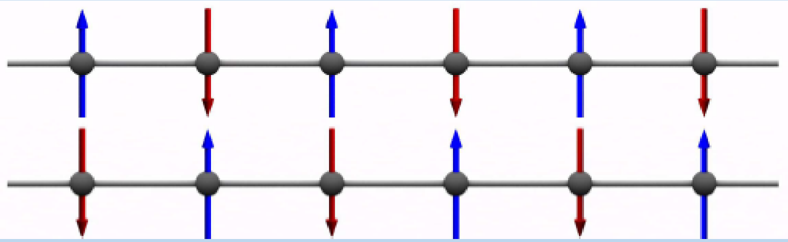
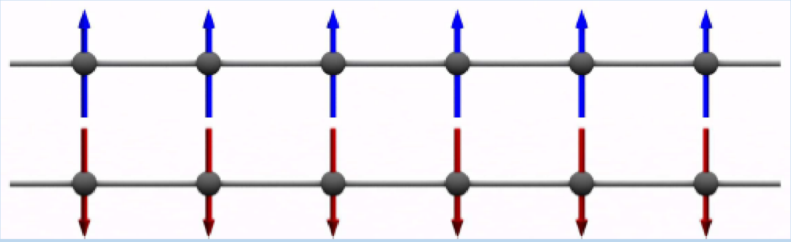


Incomplete DOS suppression & "V-shaped" low-energy DOS

Unconventional superconductivity

2D magnetic materials

Examples

	Interlayer	
Intralayer	Antiferromagnetic	Ferromagnetic
Ferromagnetic	$J<0$; $J_L>0$  $CoPS_3$ Ref[1] $MnPS_3$ Ref[2-5] $NiPS_3$ Ref [6-8]	$J>0$; $J_L>0$  CrI_3 (bulk) Ref [9,10] $CrBr_3$ (bulk, few layers) Ref[11,12] $Cr_2Ge_2Te_6$ Ref[13,14] Fe_3GeTe_2 Ref[15,16] VSe_2 Ref[17-19]
Antiferromagnetic	$J<0$; $J_L<0$  $FePS_3$ Ref[20,21] $MnPSe_3$ Ref[35]	$J>0$; $J_L<0$  CrI_3 (few layers) Ref[22] $CrCl_3$ (bulk) Ref[37]

Green – semiconductor materials; orange - metallic

Does magnetism persists in 2D magnetic materials?
How can we probe it? Is there new physics?

We will discuss experiments on one compound: CrI_3

Magneto-optical Kerr effect

Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit

Bevin Huang[1]*, Genevieve Clark[2]*, Efrén Navarro-Moratalla[3]*, Dahlia R. Klein[3], Ran Cheng[4], Kyle L. Seyler[1], Ding Zhong[1], Emma Schmidgall[1], Michael A. McGuire[5], David H. Cobden[1], Wang Yao[6], Di Xiao[4], Pablo Jarillo-Herrero[3] & Xiaodong Xu[1,2]

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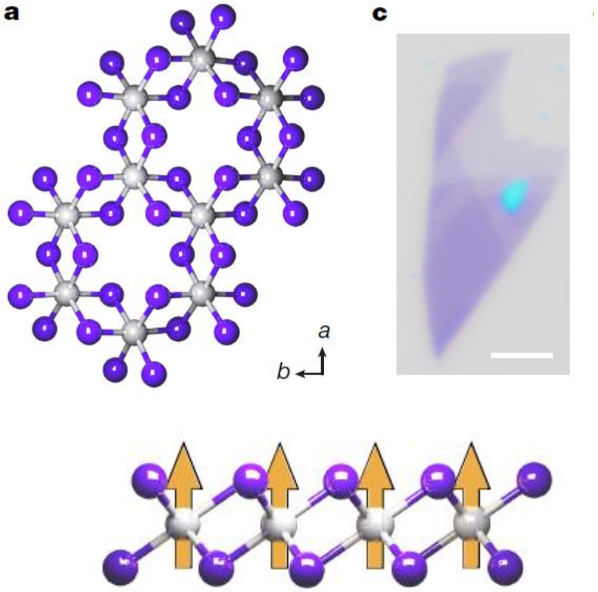
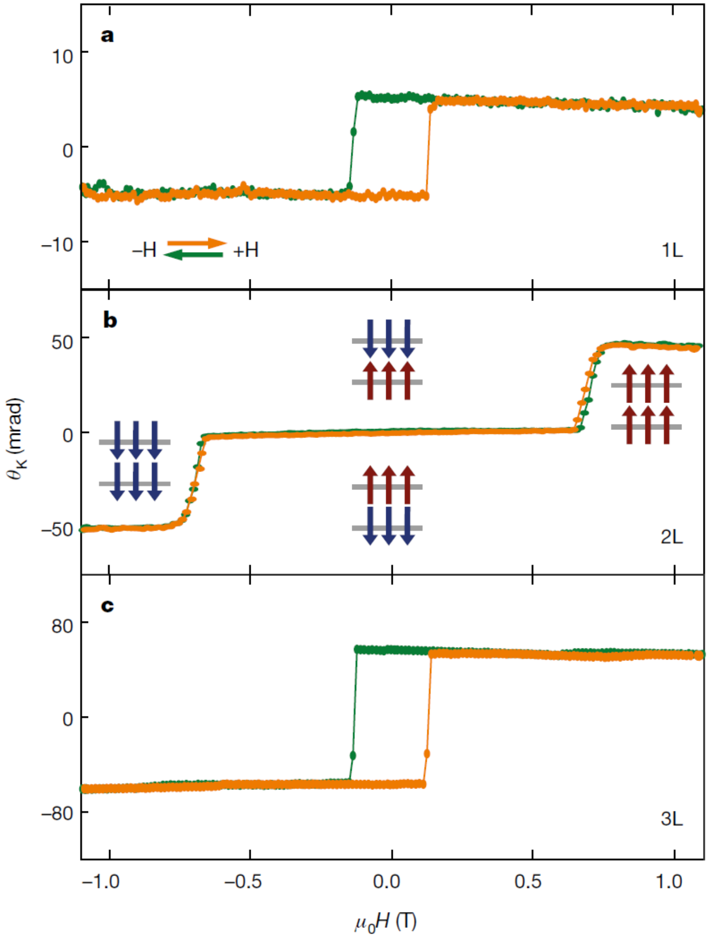
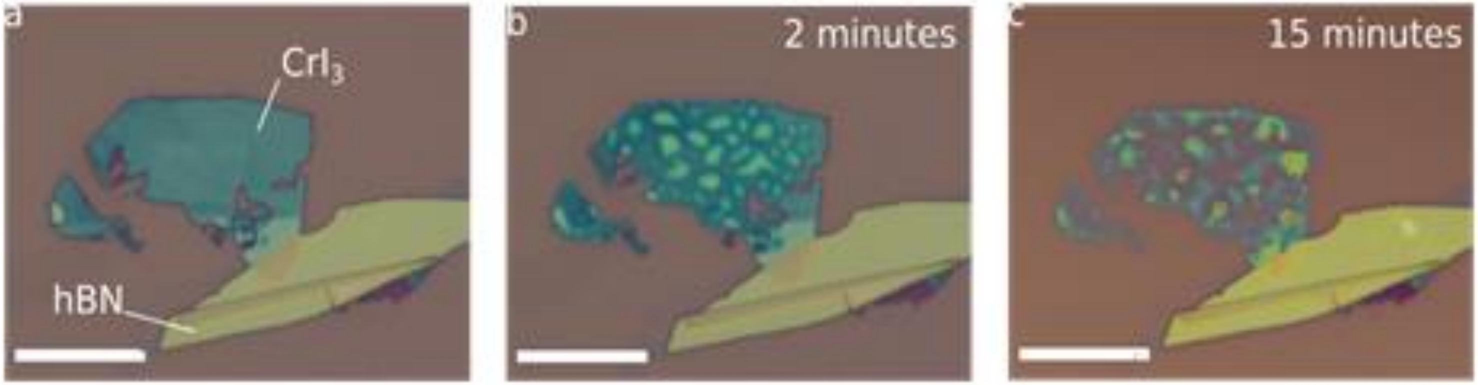




Hysteretic Kerr rotation angle as expected for ferromagnets

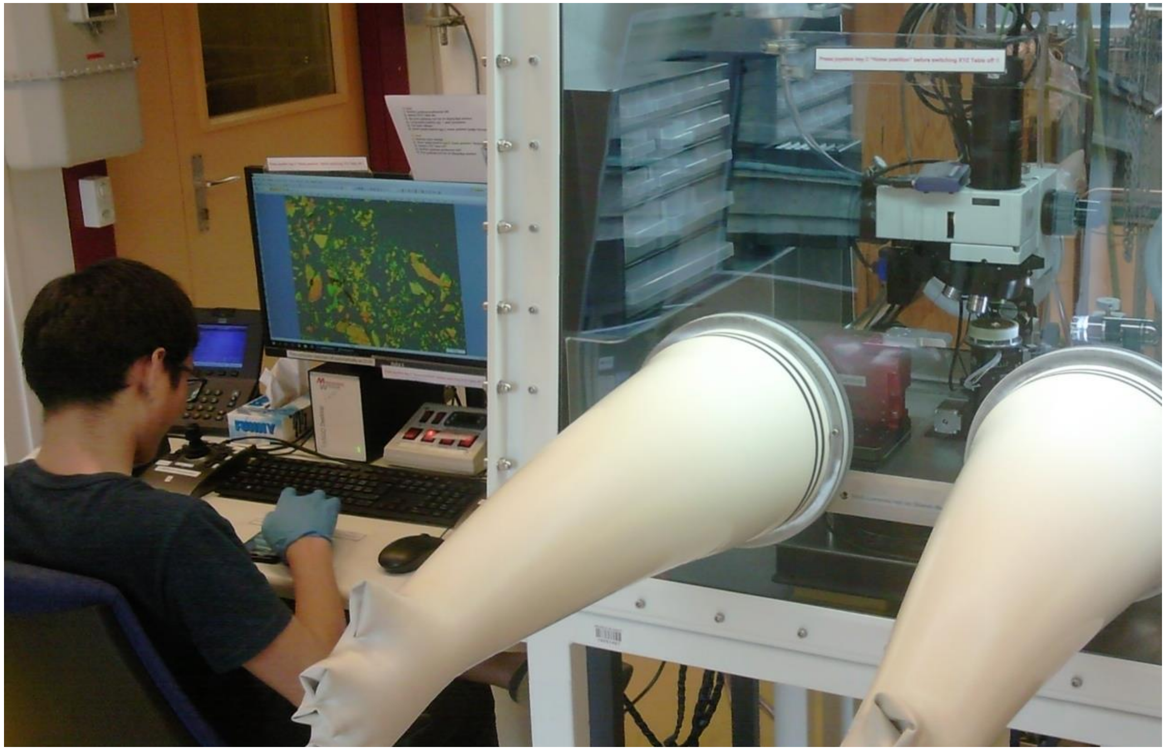
But note: Kerr effect probes broken symmetries not magnetization

Exfoliating/processing/encapsulating in Glove box

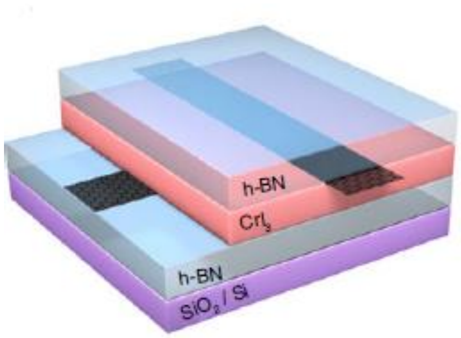


Extremely unstable in air:

Thin crystals (even 50 nm) dissolve in a few minutes

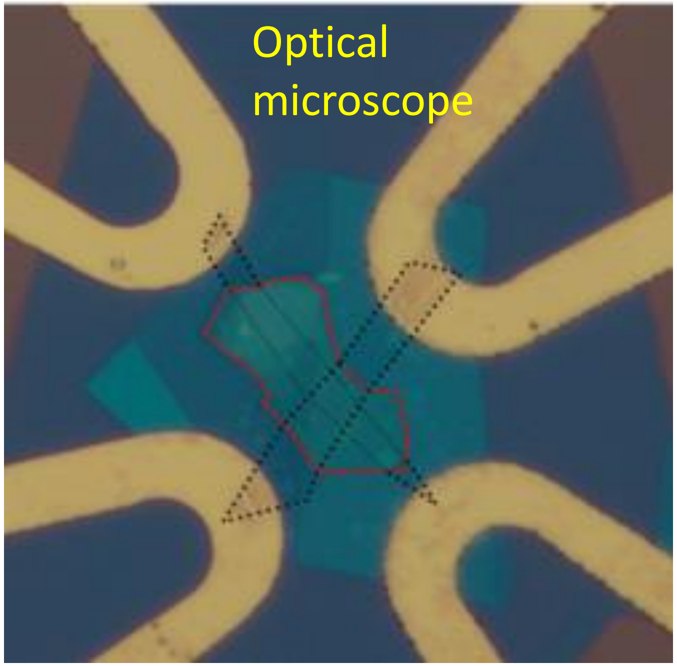


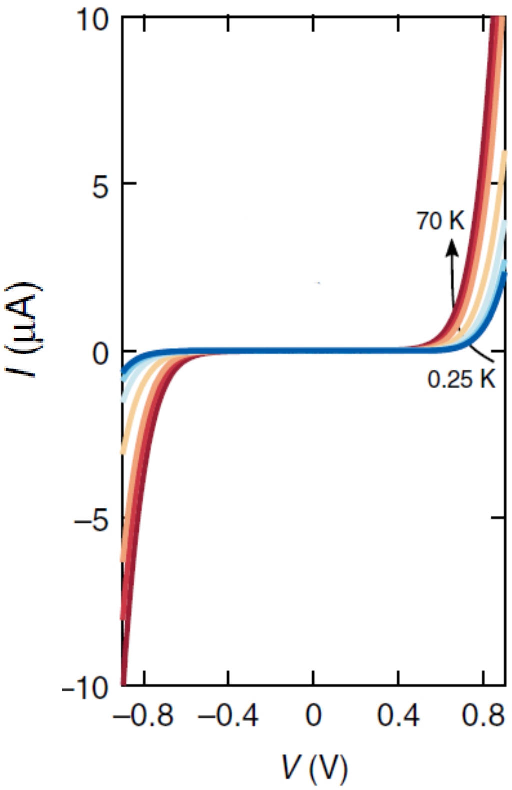
CrI3 tunnel barriers

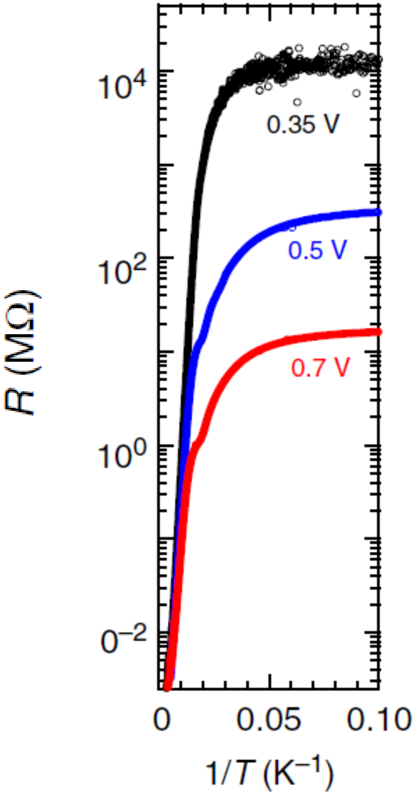


Thin CrI_3 as tunnel barrier
between graphene contacts

Tunneling

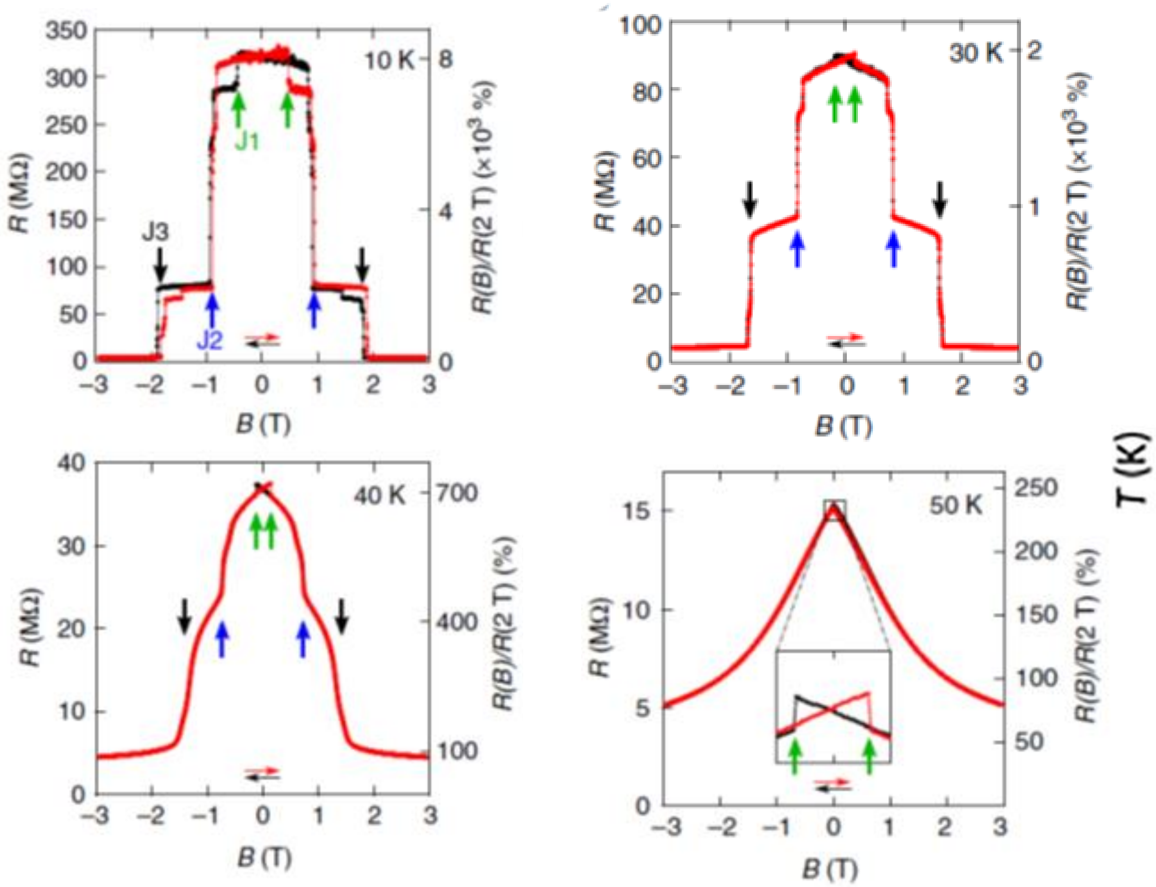


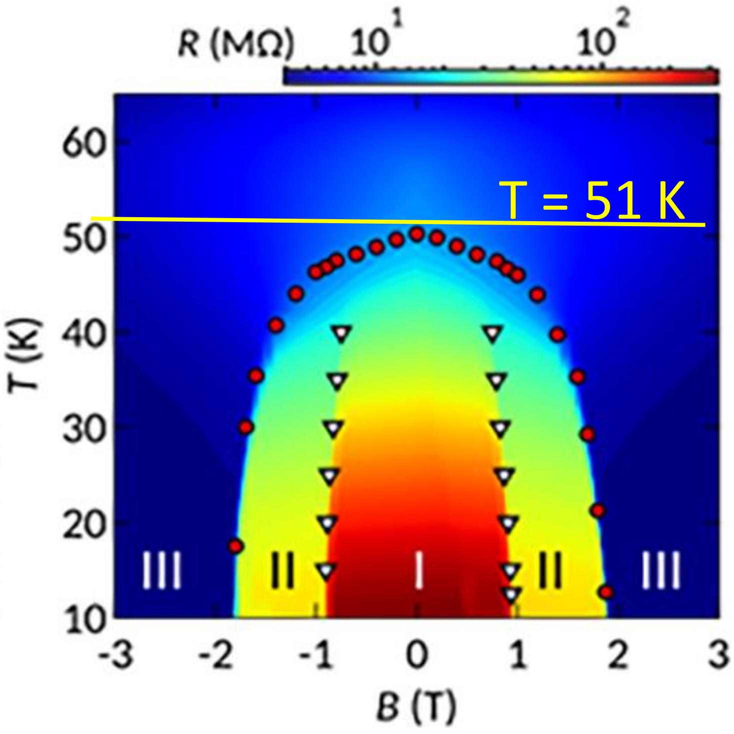




Tunneling Magnetoresistance

Giant tunneling magneto-resistance: 100 x at B = 2T



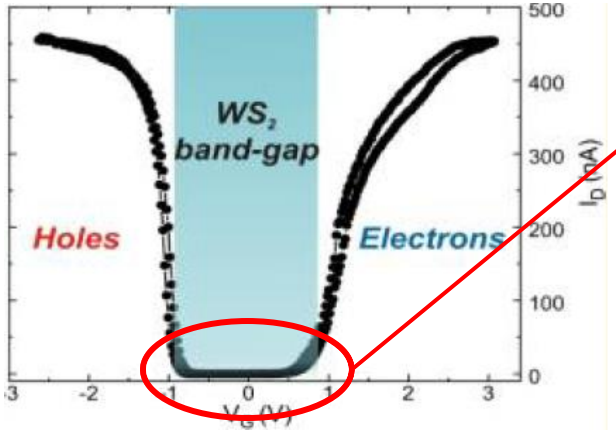


For comparison:
common tunneling spin-valves = 2 x

Extracting magnetic phase diagram from tunneling magnetoresistance

Monolayer WTe_2: topological insulator with edge transport

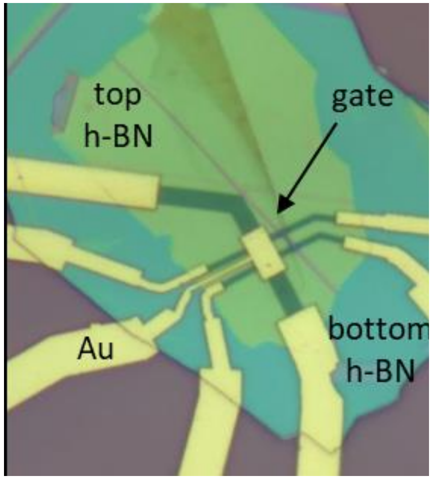
WS_2 = Semiconductor = trivial insulator

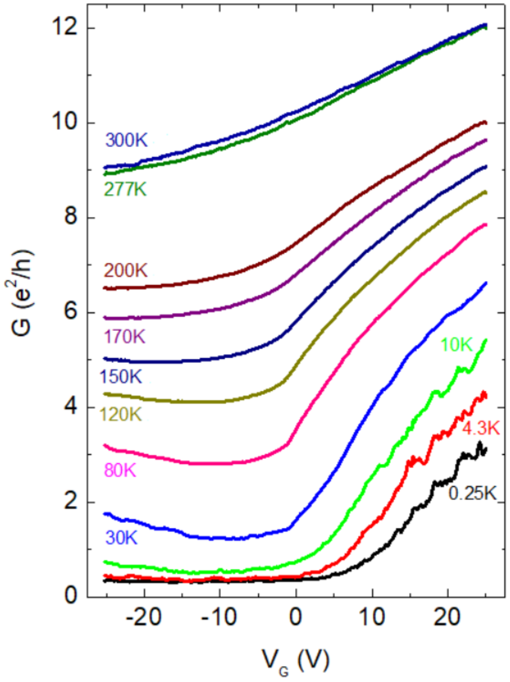


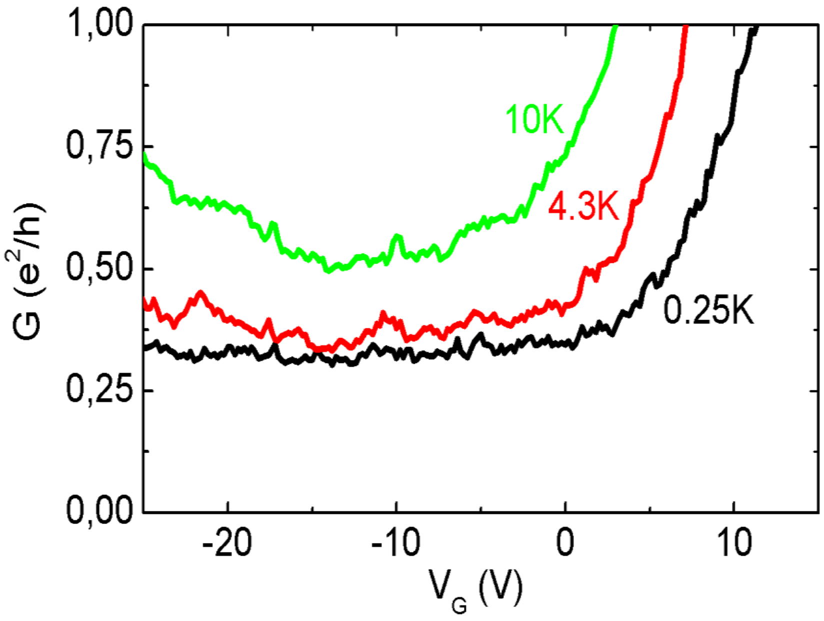
Conductance vanishes

(exponentially small $\propto e^{-\frac{\Delta}{2kT}}$)

WTe_2 = topological insulator





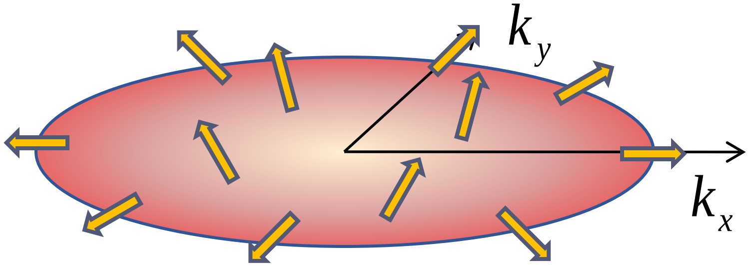


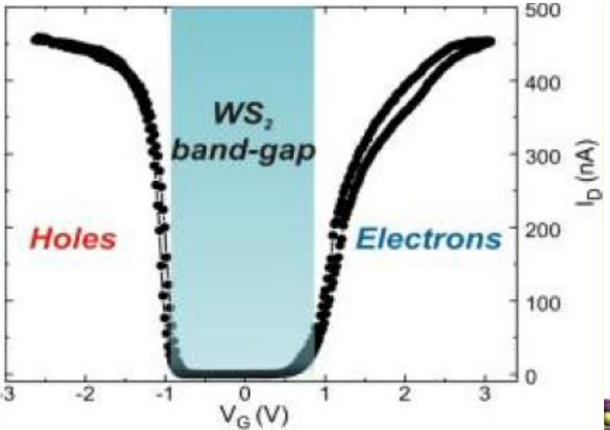
Conductance at low T:

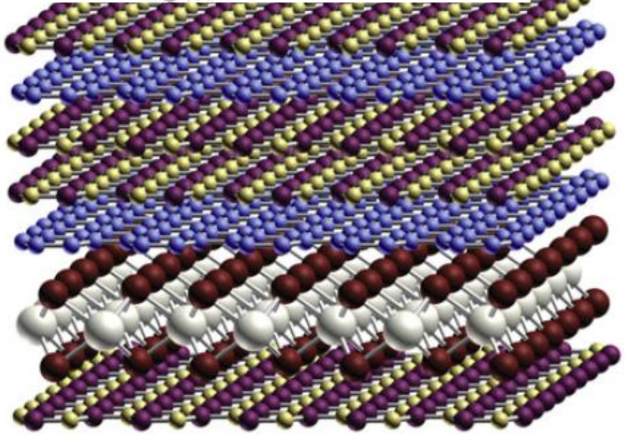
$$G \sim \frac{e^2}{h}$$

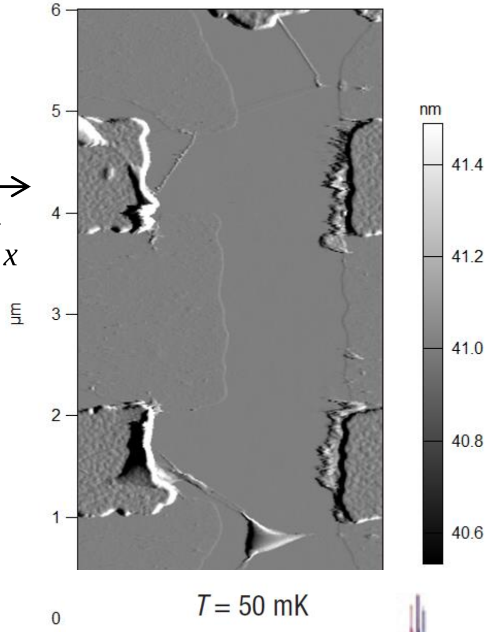
Topological insulator = Edge conductance

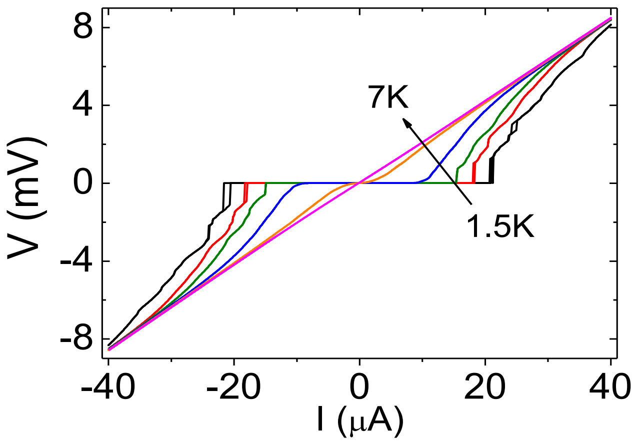
The exploration of atomically thin crystals has only just started

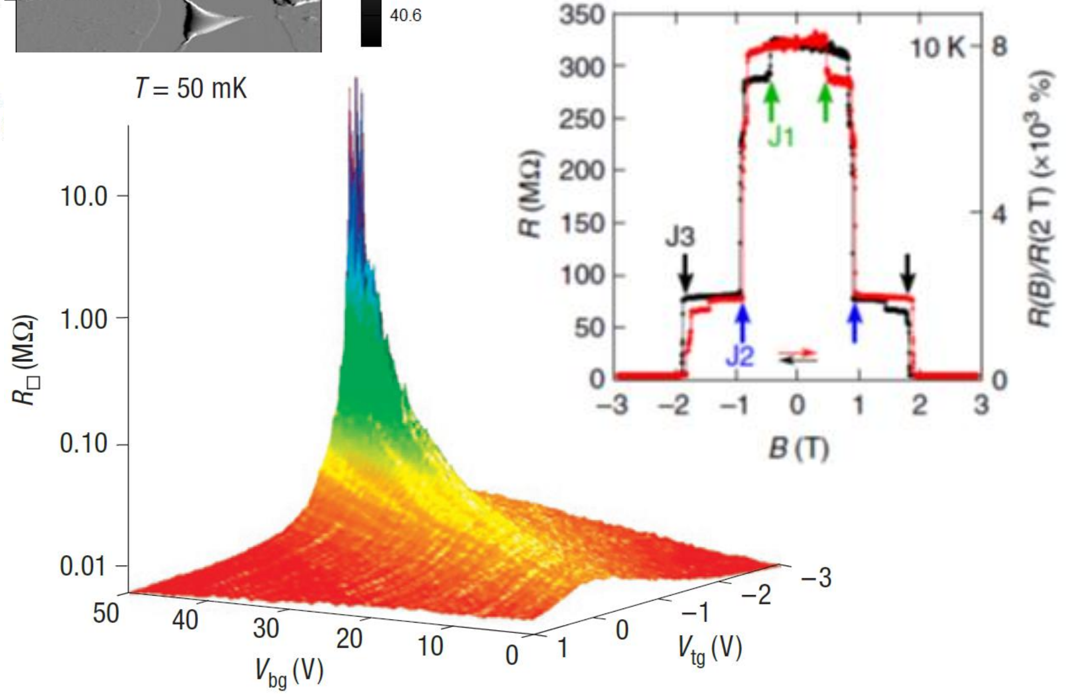












This is a vast and largely unexplored field of research