



Studying the flow of electrons in 2D materials

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arXiv:1902.04264 , Nature Communications 8, 14518 (2017)
and Physical Review Letters 121, 056801 (2018).

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www.tifr.res.in/~nano

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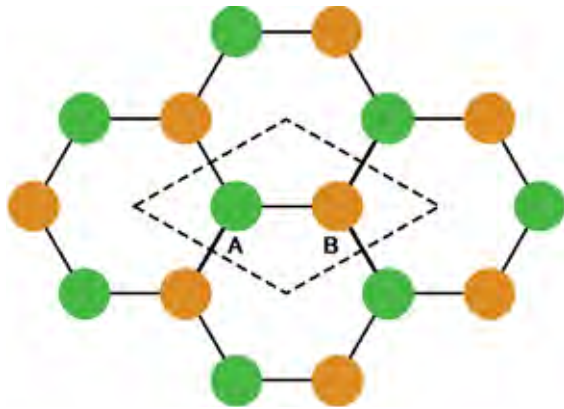
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Outline

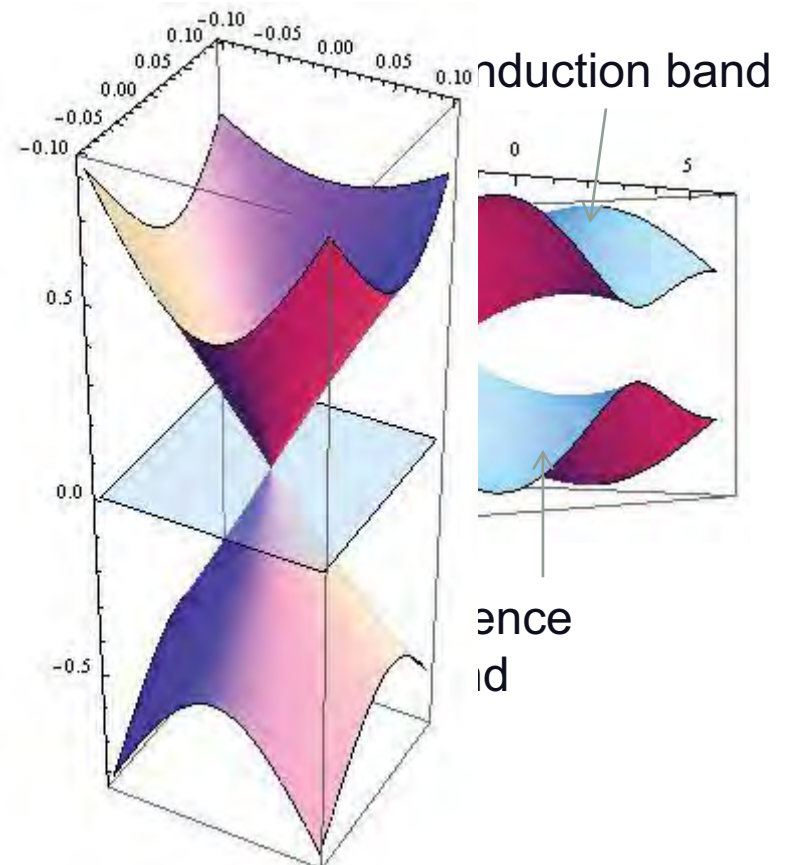
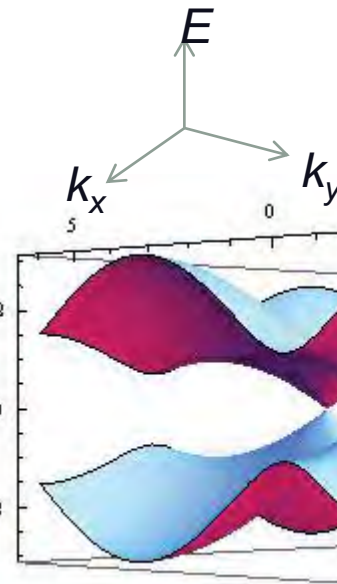
- Graphene basics
- What is exciting about graphene based 2D devices?
- Our experiments probing Berry's phase in multiband system
- Summary

Graphene basics

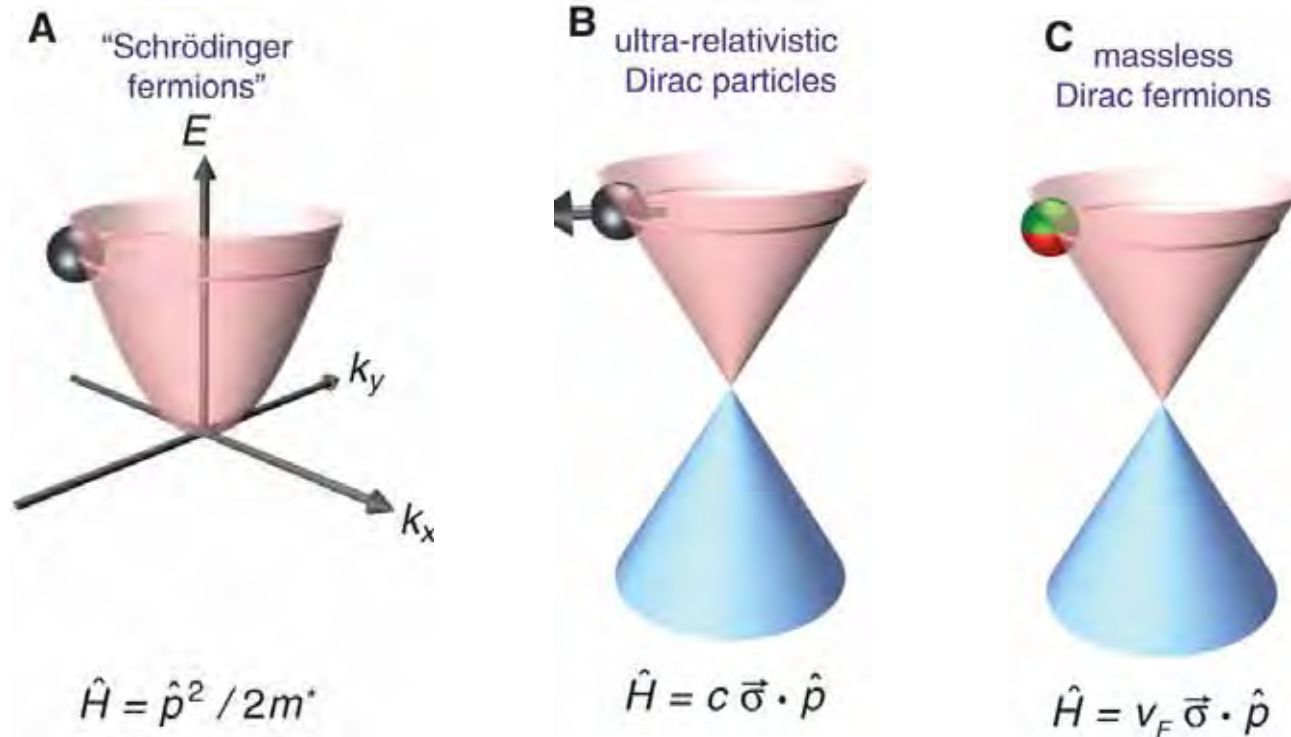


- Bravais lattice with two carbon atom basis

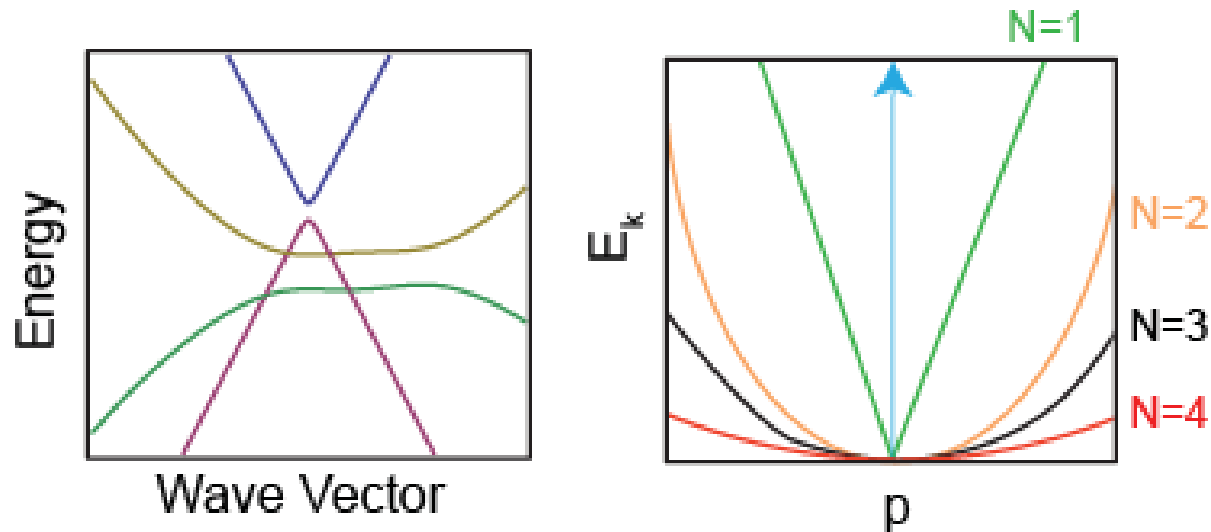
- Two bands meet at a point
- For undoped graphene E_F energy lies exactly at the point
- Linear dispersion



What is different from the rest of solid state physics?

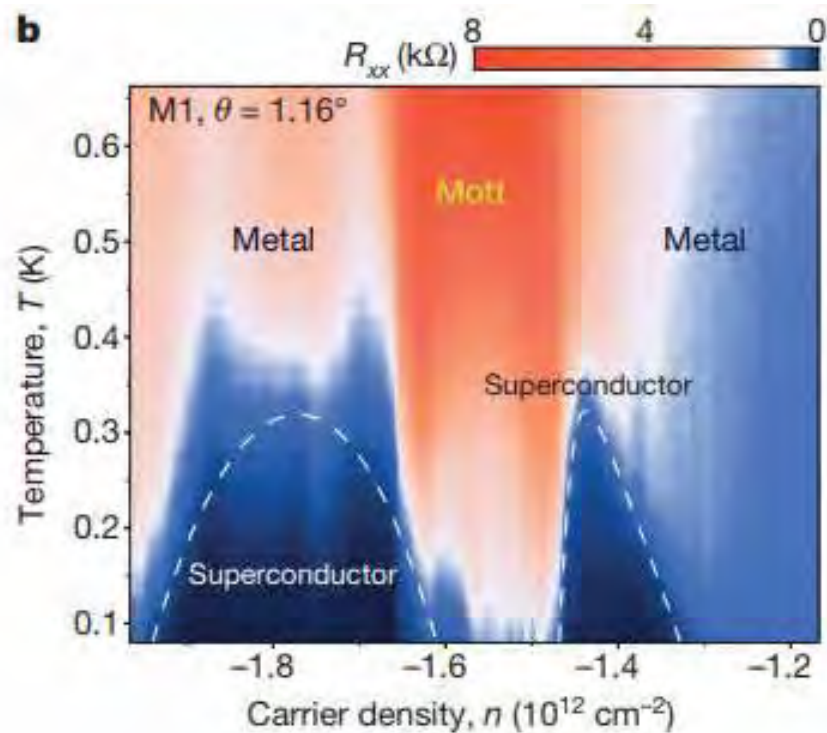
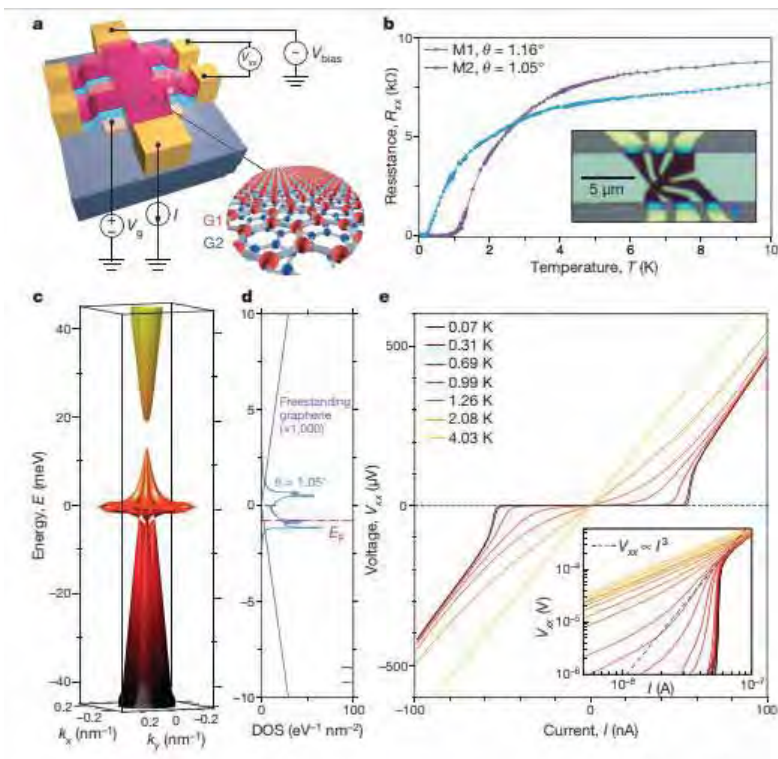


Why few layers of graphene are interesting?

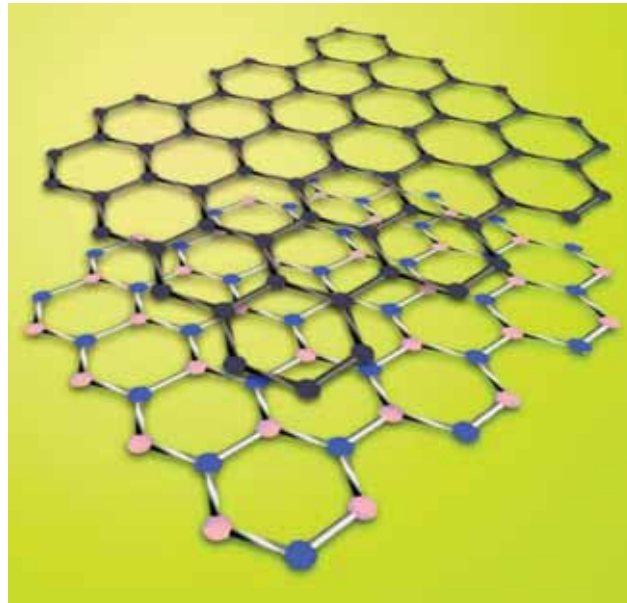


- Interactions become more important for multiple layers due to flatter bands
- Tunable symmetries
- Possibility of studying non-Abelian states quantum Hall states

Why are 2D materials exciting?



Breaking symmetry in monolayer graphene – going from a semimetal to an insulator



<https://phys.org/>

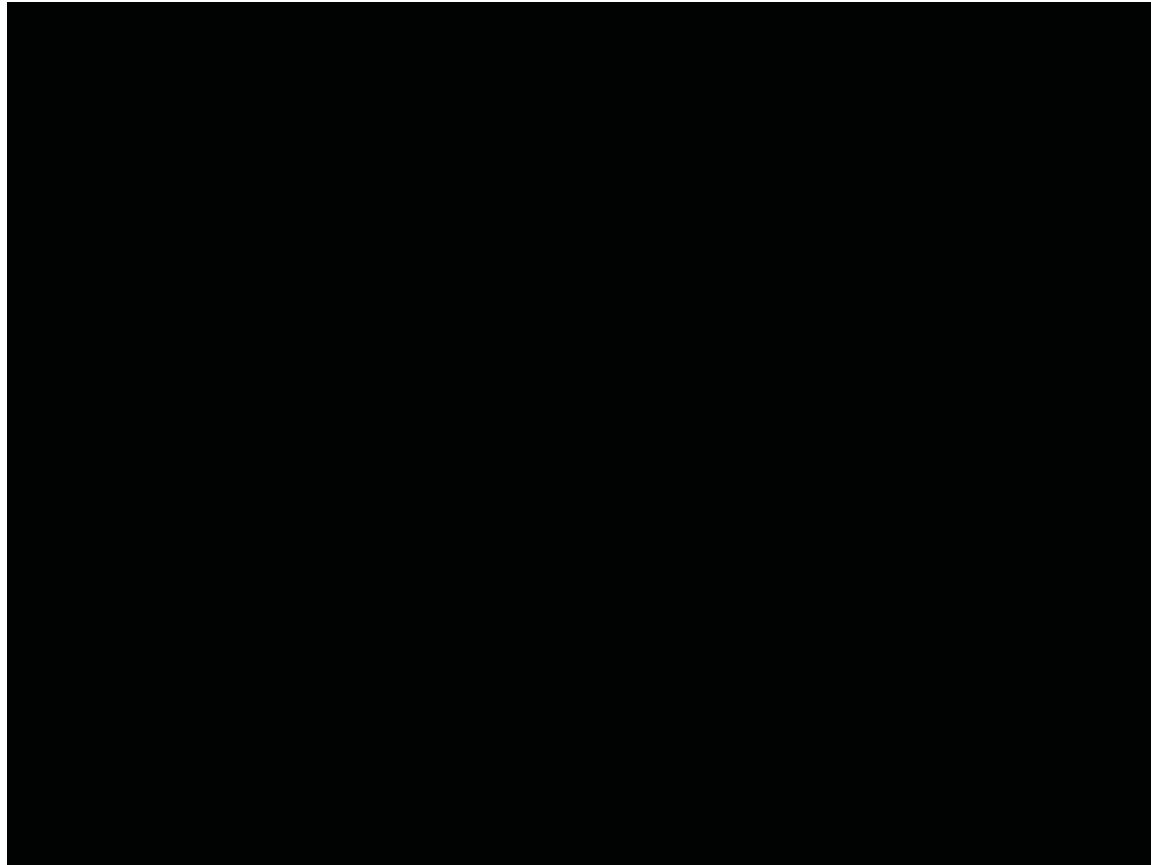
Graphene

$$H_{\mathbf{K}} = v_F \boldsymbol{\sigma} \cdot \mathbf{p}$$

Boron Nitride or MoS₂

$$H_{\mathbf{K}} = v_F \boldsymbol{\sigma} \cdot \mathbf{p} + \Delta \sigma_z$$

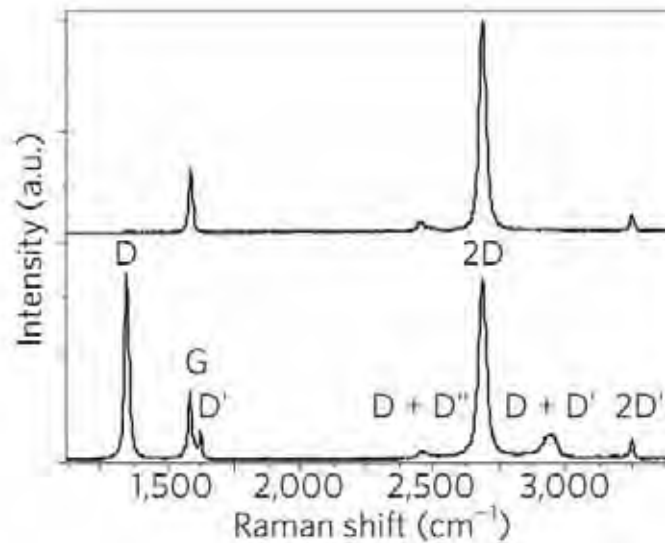
How to make peel graphene using exfoliation?



Ozyilmaz group at NUS Method used by Novoselov and Geim for the first experiment.

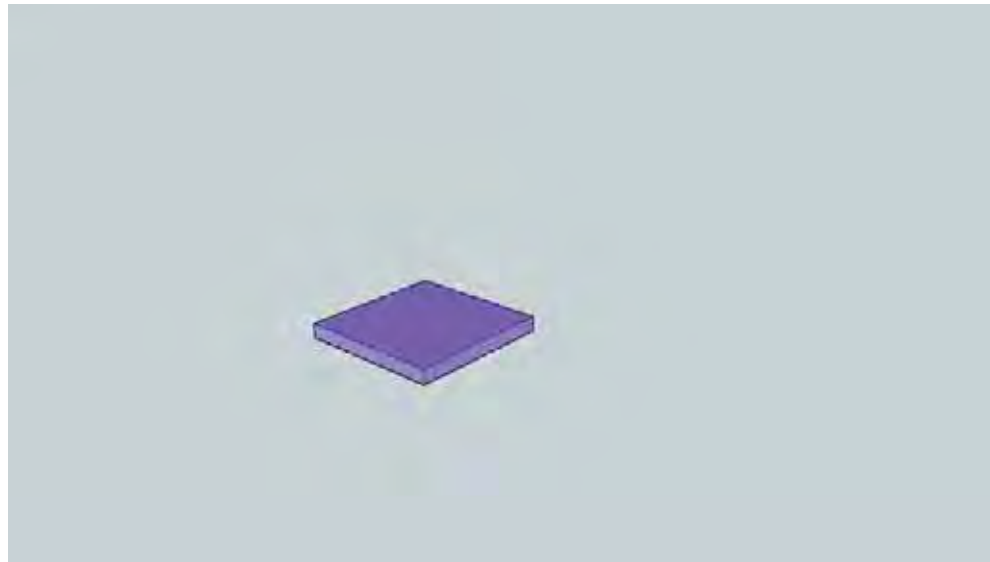
Tests for one unit cell of 2D materials

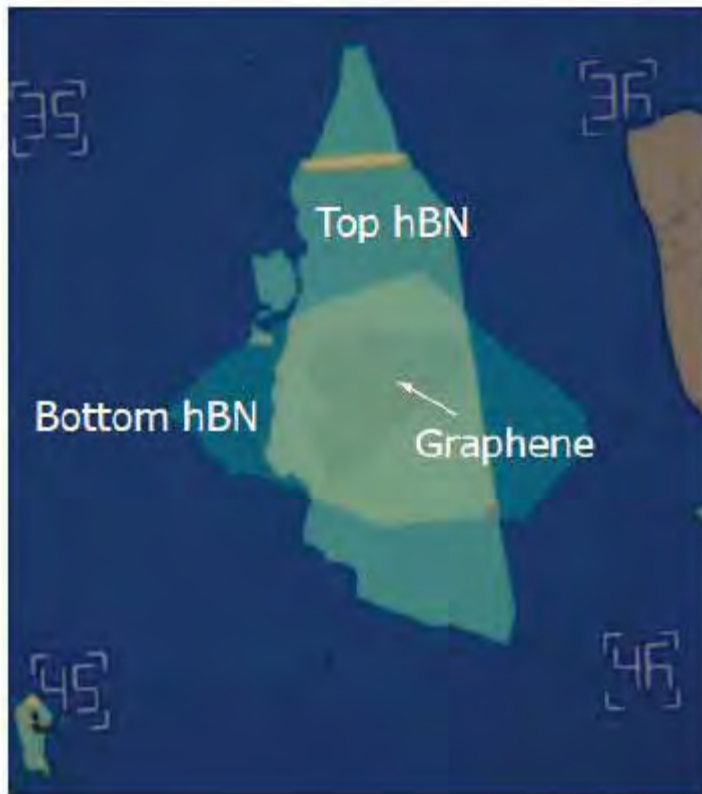
Raman scattering



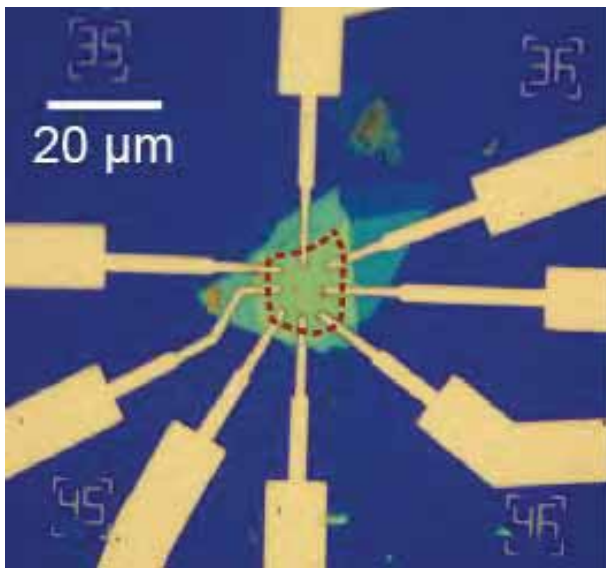
Review: Ferrari et al.,
Nature Nanotechnology (2013).

How does one contact nanoscale structures?



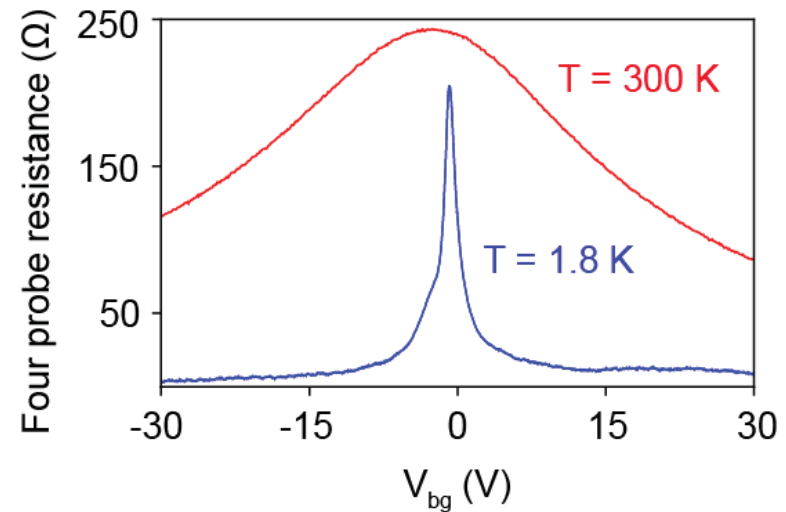


Device fabrication and characterization



Optical image of the device

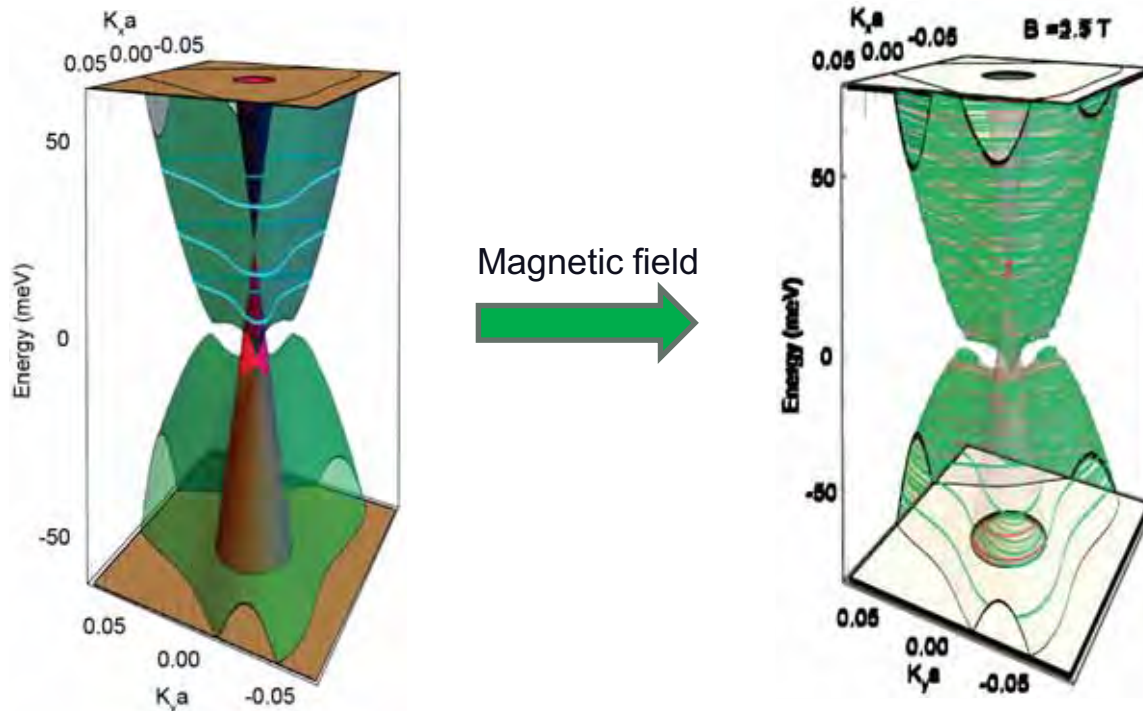
Similar to L. Wang, *Science* 342, 614 (2013) with some modification



At density $n = 2 \times 10^{12} \text{ cm}^{-2}$ ($30 V_{bg}$)

- Mean free path $\sim 8 \mu\text{m}$
- Mobility $\sim 500,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$

Landau levels and Berry's phase

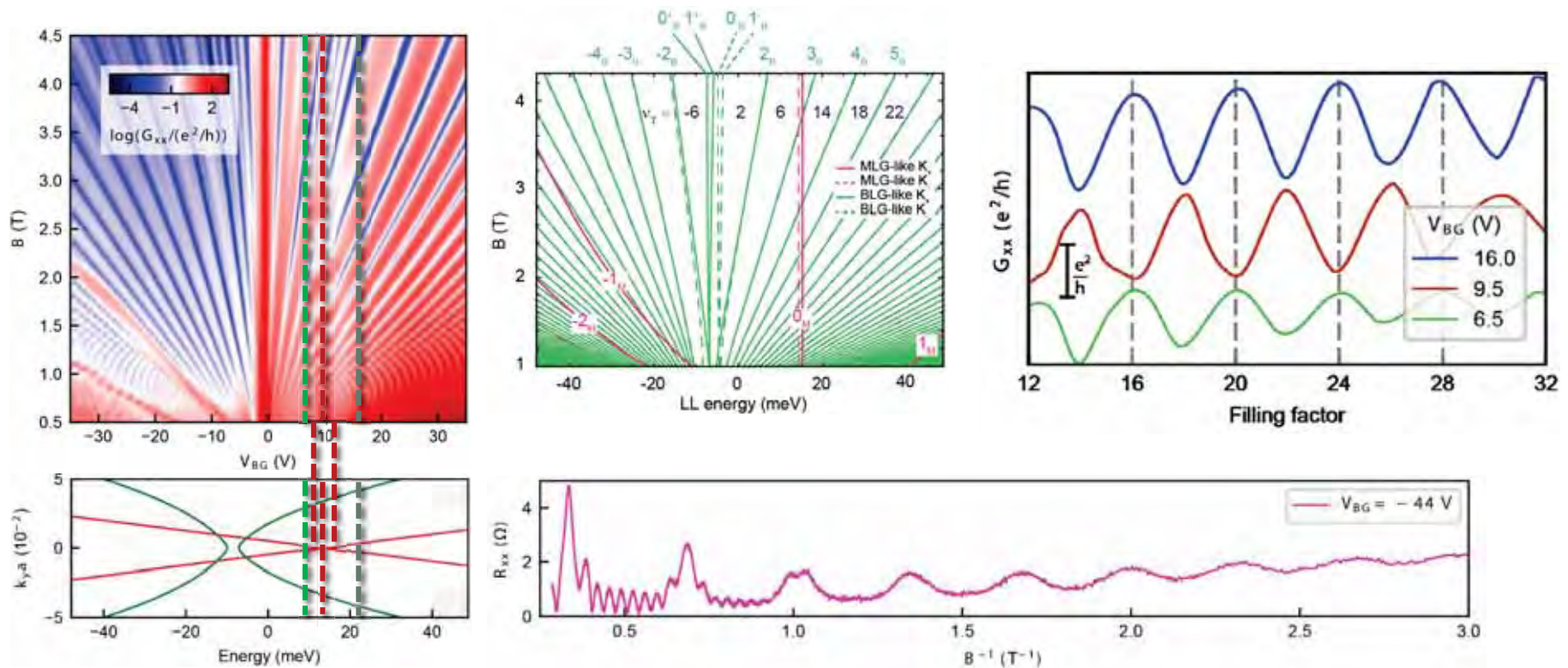


$$S(\varepsilon, k_z) = \left(\frac{2\pi|e|H}{\hbar c} \right) (n + \gamma)$$

$$\gamma - \frac{1}{2} = -\frac{1}{2\pi} \oint_{\Gamma} \Omega d\mathbf{k}$$

Mikitik and Sharlai
Phys. Rev. Lett. 82 2147 (1999)

Berry's phase in multiband system



- Two SdH frequency results from two Fermi surfaces
- Probe consequences of Berry's phase in a multiband system

Summary

- Graphene basics
- What is exciting about graphene based 2D devices?
- Our experiments on Berry's phase in multiband system