Epitaxial Graphene Devices for Scanning Probe Measurements

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Outline

Introduction

•Dissipationless current

•Graphene on SiC

Goal

•Scanning Gate Microscopy

Mono- and bilayer composite devices in the Quantum Hall regime

•Device configuration

•Raman map & atomic force microscopy image

•Transport measurements

•Conductance calculation

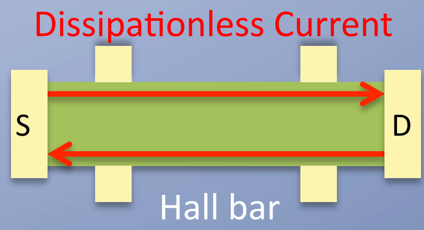
Summary

Introduction

Dissipationless current

Edge current flows in quantum Hall regime

Controlling dissipationless current → future low-energy consumption devices

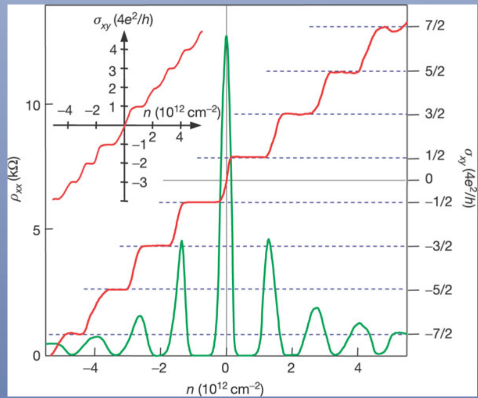


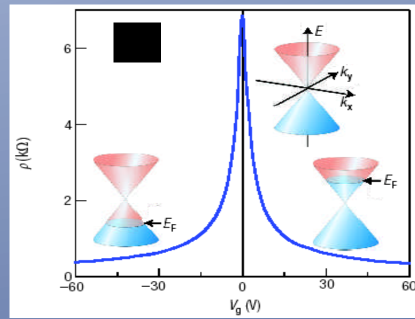
Why graphene?

·Clear quantum Hall effect is observed

·High mobility

·Filling factor differs between mono- and bilayer graphenes

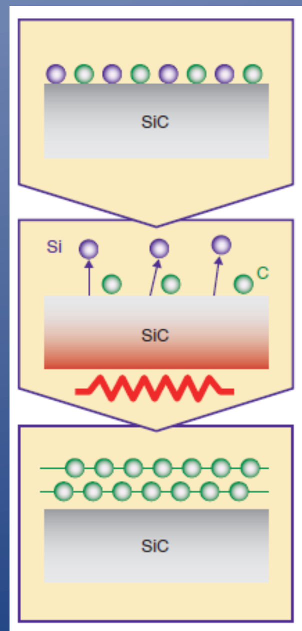




Graphene on SiC

Epitaxial growth by Si sublimation technique

large area, high quality, insulating substrate



A. K. Geim and K. S. Novoselov, Nature Mater. 6, 183 (2007)

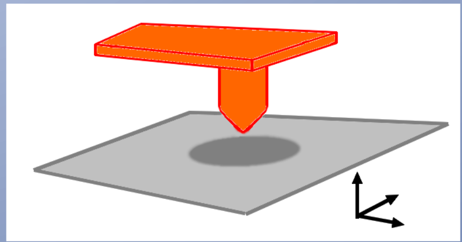
K. S. Novoselov et al., Nature 438, 197 (2005)

Y. Zhang et al., Nature 438, 201 (2005)

Hiroki Hibino et al., NTT Technical Review 8,(2010)

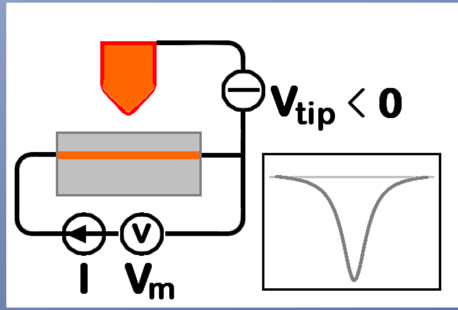
Goal: Scanning Gate Microscopy

A voltage-biased AFM tip is scanned above a sample surface. This creates a perturbation below the tip, which locally modifies the potential landscape of a device (typically 2DEGs, graphene, nanowires).



Scanning Gate Microscopy: low-T, high-B AFM
Topographic imaging + movable electrostatic gate

→ **2D imaging of transport properties**

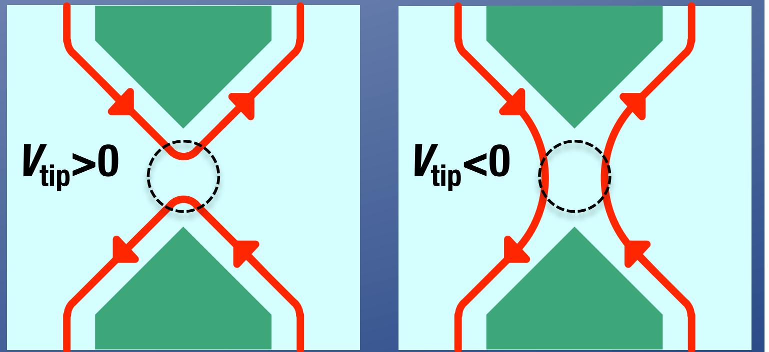


Space information: G(x,y)

Extension / space distribution of electronic states
Relevant length scales (inter-channel relaxation length)
Size-dependent effects (edge state mixing)
…

resolution	**≤ 10 nm**
stability	months
temperature	300 mK
Magnetic field	0-9 T

Side-gate structure

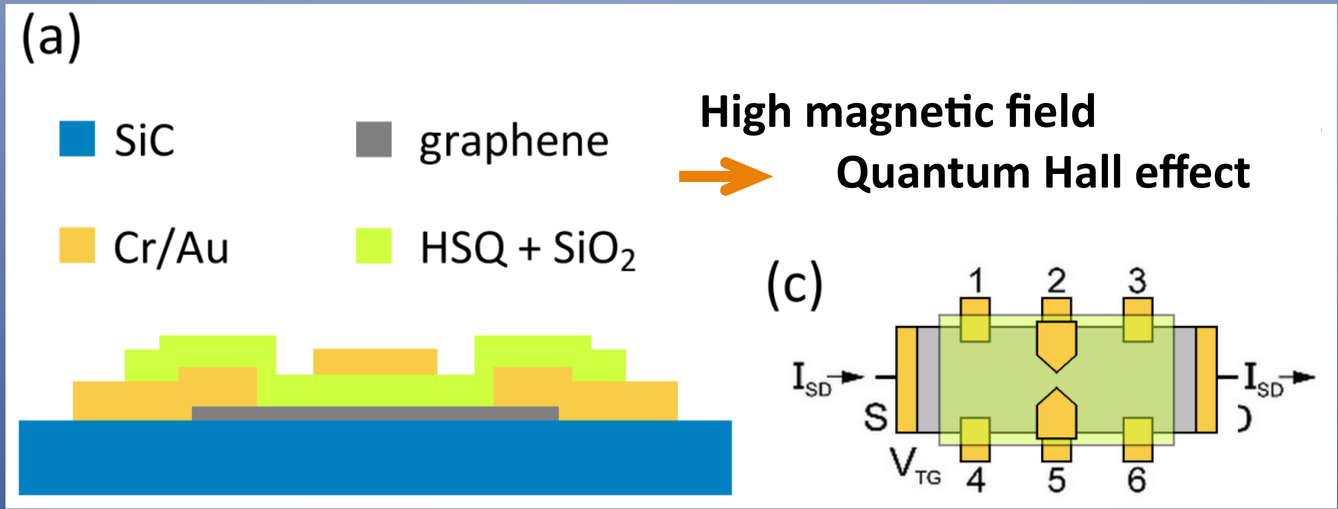


Tip voltage is applied at the center

M. A. Topinka et al., Nature 410 (2001).
R. Crook et al., Science, 312 (2006).
N. Paradiso et al., Phys. Rev. Lett., 108 (2012).

Fabrication: Side-Gated Devices

- Epitaxial graphene grown on the Si face of SiC (0001).
- Large area Hall bars (300 μm x 50 μm)
- Gate insulator: HSQ (Hydrogen Silsequioxane) (140 nm) + SiO_2 (40 nm)
- Electrode: Cr/Au (10/180 nm)

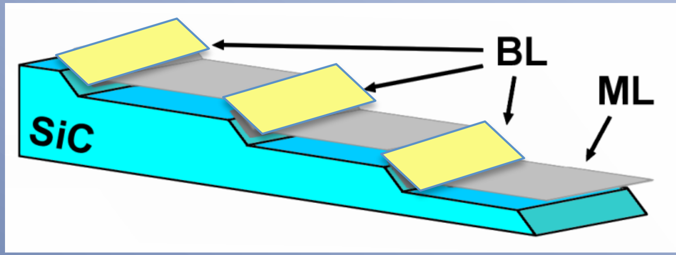


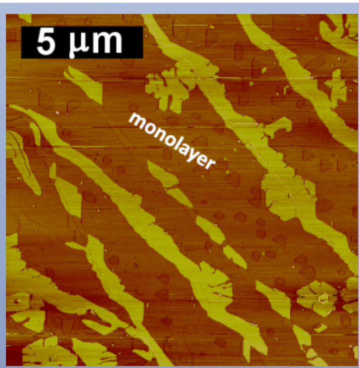
S. Tanabe, Y. Sekine, H. Kageshima, M. Nagase, and H. Hibino, Phys. Rev. B 84, 115458 (2011).

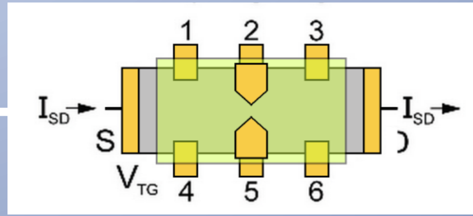
First Step

Characterization of the electric properties of the device without applying the side-gate voltage and AFM tip voltage

Sample: AFM & Raman







~ few μm wide monolayer regions on SiC terraces

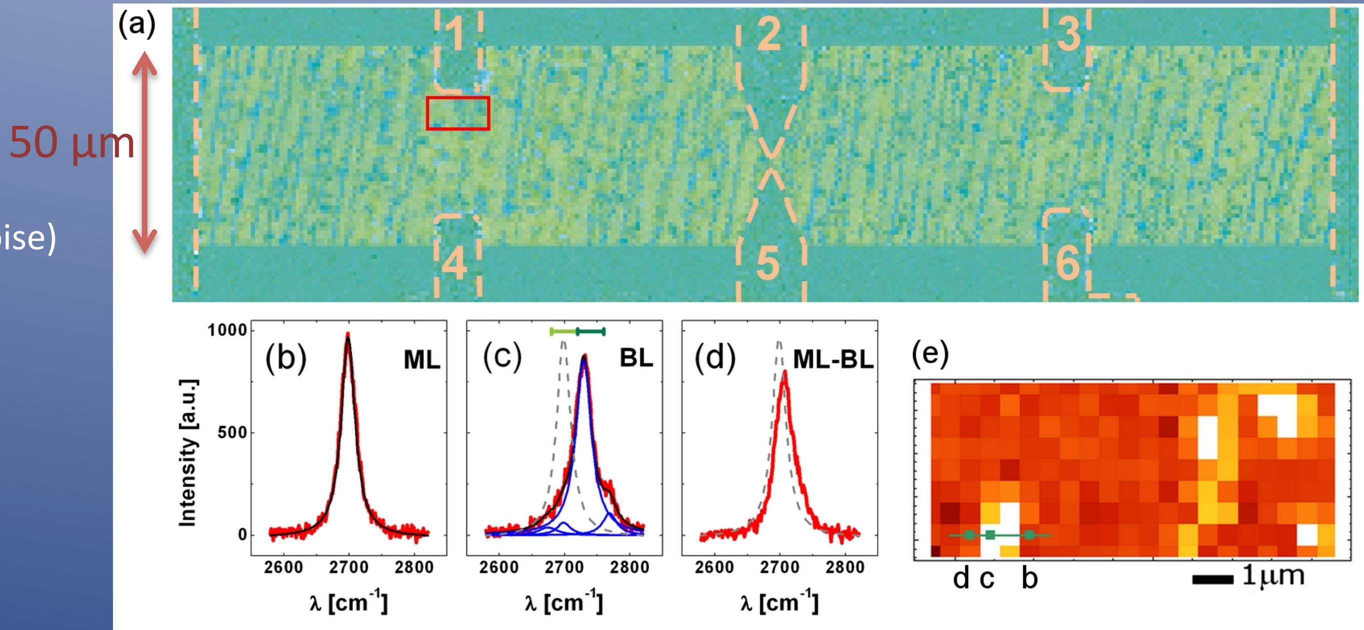
≤1 μm wide bilayer domains along step edges

Raman spectra @ Room Temperature

(Renishaw Micro-Raman)
514 nm laser excitation
spot diameter < 1 μm.
step-size of 0.5 μm
integration times up to 10 s (low noise)

Monolayer: single Lorentzian
→ 2680-2720 cm^{-1}

Bilayer: 4 Lorentzians
→ 2720-2760 cm^{-1}



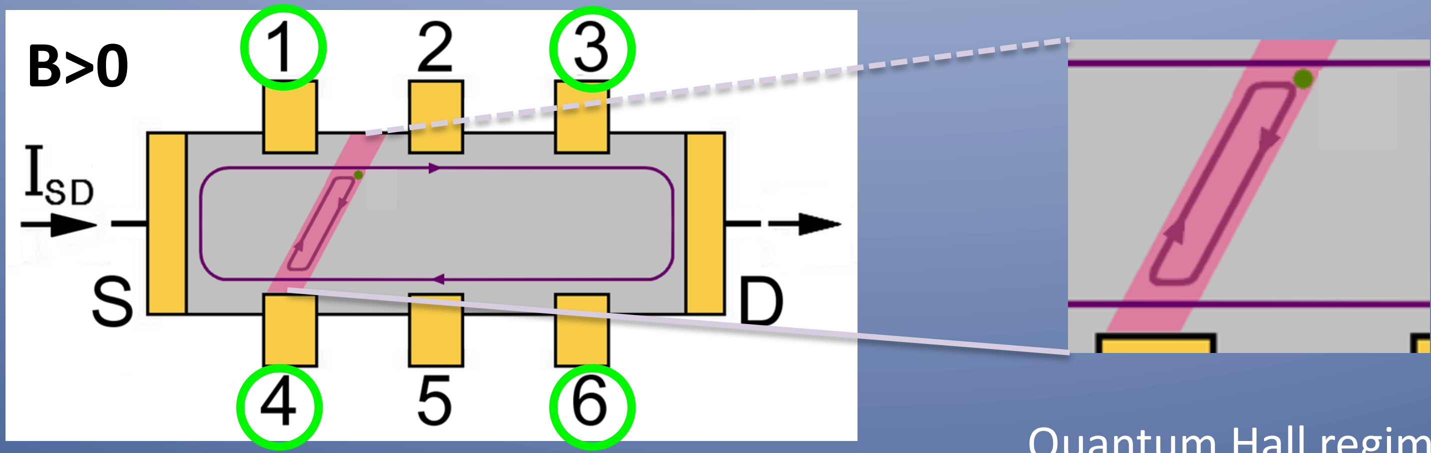
The Hall bar is intersected by tens of SiC step edges, onto which elongated bilayer domains are present.

→ Bilayer stripe connect one side of the device to the other

Configuration of mono- and bilayers

From the experimental results of magnetoresistance

Bilayer stripe (red) crossing Hall bar



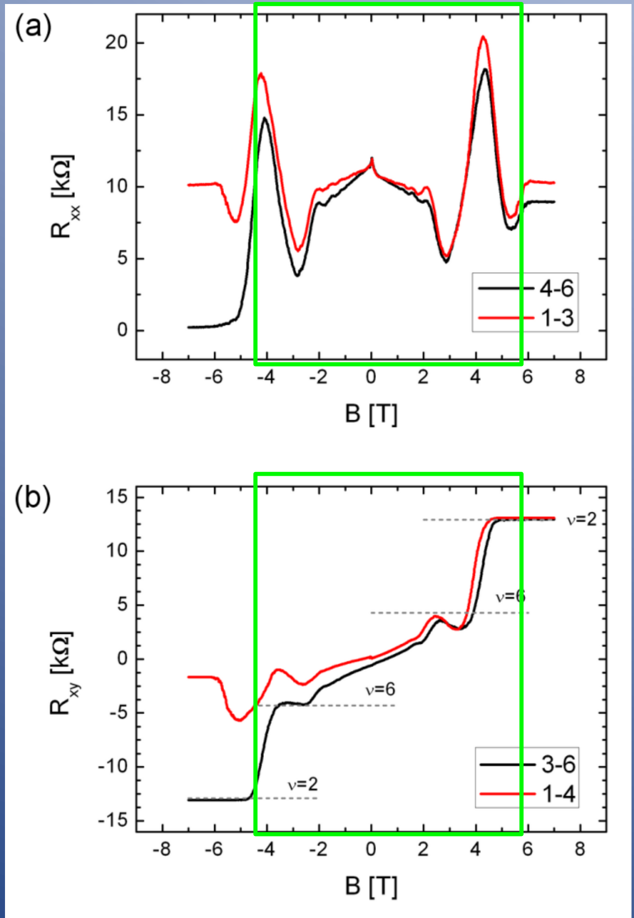
Quantum Hall regime

longitudinal resistance R_{xx}: $R_{1\text{-}3}$, $R_{4\text{-}6}$

transverse resistance R_{xy}: $R_{1\text{-}4}$, $R_{3\text{-}6}$

Magnetoresistance (1): Low Magnetic Field

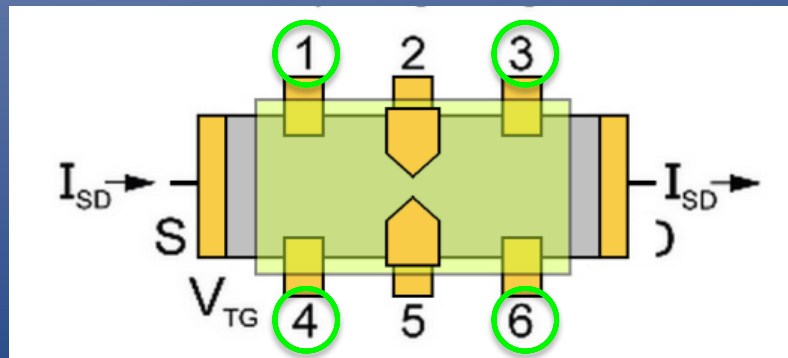
@ 250 mK



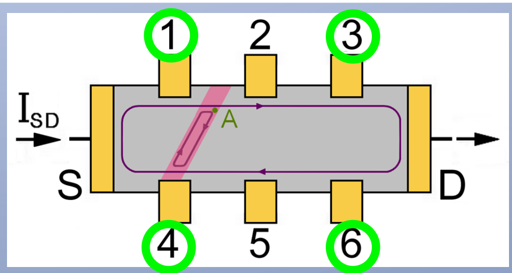
|B| < 5 T Conventional quantum Hall effect of monolayer graphene

longitudinal resistance Rxx:
similar at both device sides;
typical behavior expected for clean monolayer:
weak localization around B=0;
magneto-oscillations (precursory to the Shubnikov-de Haas).

transverse resistance Rxy:
similar for both contact pairs;
monotonous dependence;
v=6 plateau.

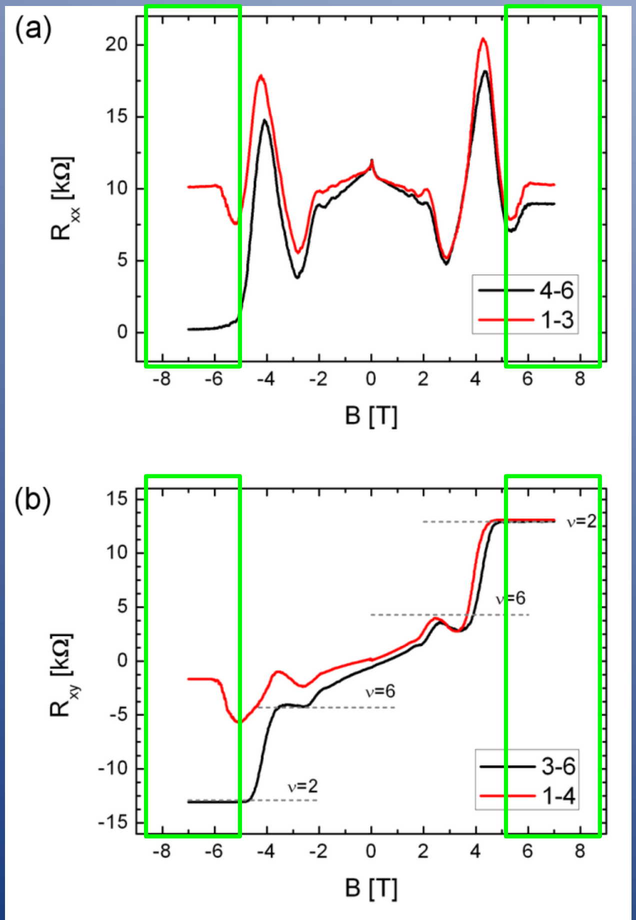


Magnetoresistance (2): High Magnetic Field



Bilayer stripe (red) crossing Hall bar

@ 250 mK



|B| > 5 T Anomalous Quantum Hall effect

longitudinal resistance Rxx:

1-3 : **invariant** to inversion of B; **R ≈ 10 kΩ**

4-6 : **asymmetric** upon inversion of B ; SdH for B<0 only

transverse resistance Rxy:

3-6 : conventional (**symmetric**) half-integer QHE; ν=±2 plateaus

1-4 : **asymmetric** upon inversion of B ; $R_{1\text{-}4}$=-1.6 kΩ for B<0

1. **B-dependent effect**
2. **Flat resistance values**
3. **Peculiar asymmetry**

Configuration of mono- and bilayers

1. Effect dependent on B
2. Flat resistance values

→

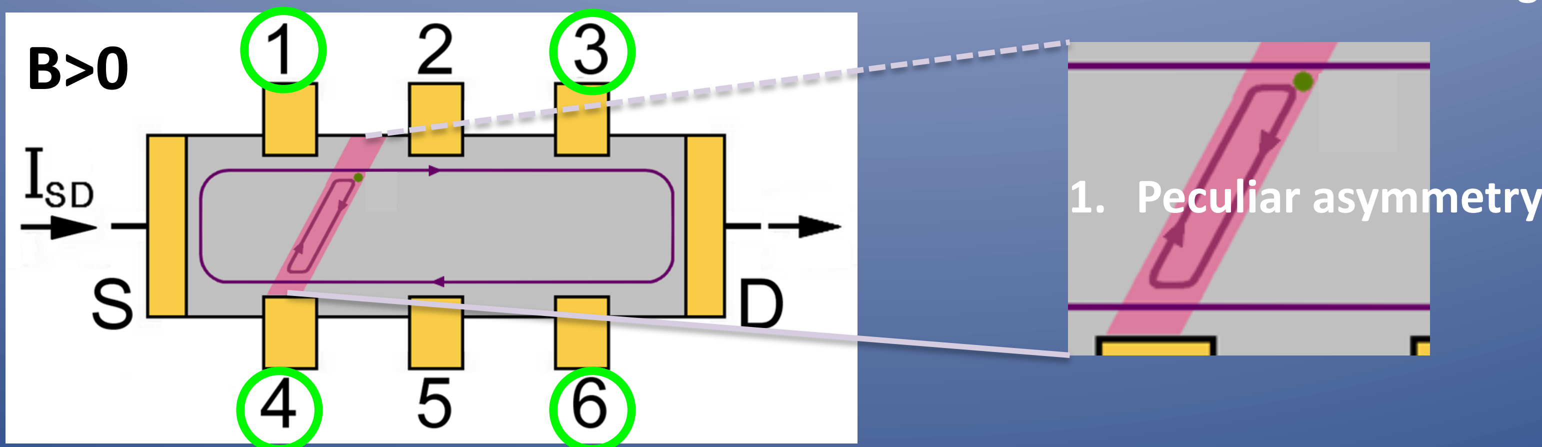
1. Quantum Hall Effect
2. Anomalous quantized plateaus

→ Quantum Hall effect Involving edge channels in **bilayer**

3. Peculiar asymmetry → 3. Chirality of edge states → Only one possible configuration

Bilayer stripe (red) crossing Hall bar

Quantum Hall regime



Filling factor

Monolayer graphene

$\nu_M = \pm 2(2n+1) = \pm 2, \pm 6, \pm 10, \cdots$

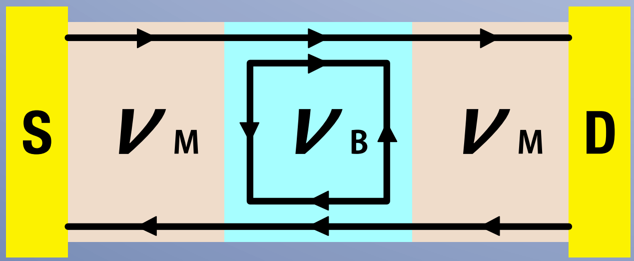
$n = 0, 1, 2, \cdots$

Bilayer graphene

$\nu_B = \pm 4n = \pm 4, \pm 8, \pm 12, \cdots$

$n = 1, 2, 3, \cdots$

Landauer-Büttiker approach



$|\nu_B| > |\nu_M|$, $\nu_B \cdot \nu_M > 0$

- Mixing of channel
- Current conservation at boundary between mono- and bilayer graphene

$I_i = e/h\,[\,(\nu - r_{ii})\mu_i + \sum T_{ij}\,\mu_j\,]$

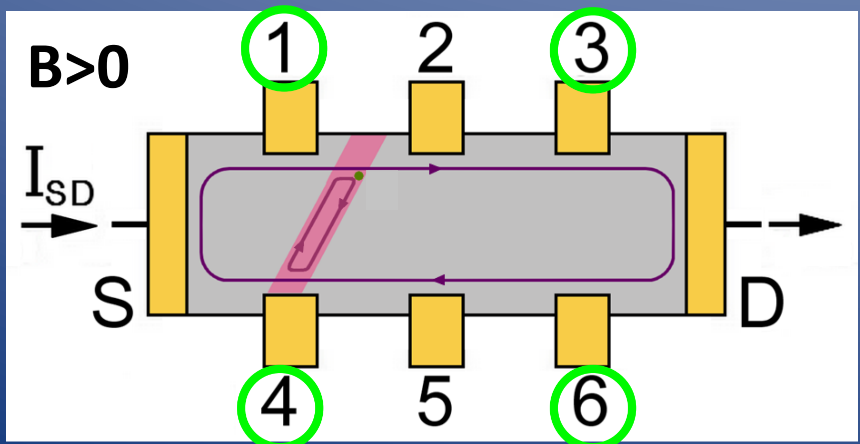
$I_S = I$, $I_D = -I$, $I_i = 0$

I_i : current

r_{ii} : total reflection coefficient at electrode i
(r_{ii} = 0 for ideal lead)

μ_i : electrochemical potential

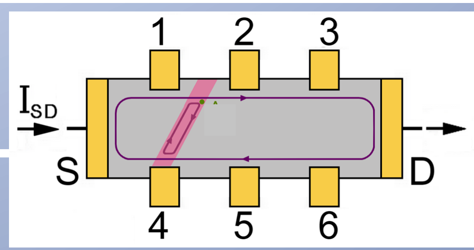
T_{ij} : total transmission coefficient from i to j electrodes
(probability ejected into ν proportional to $1/\nu$ for each electron)

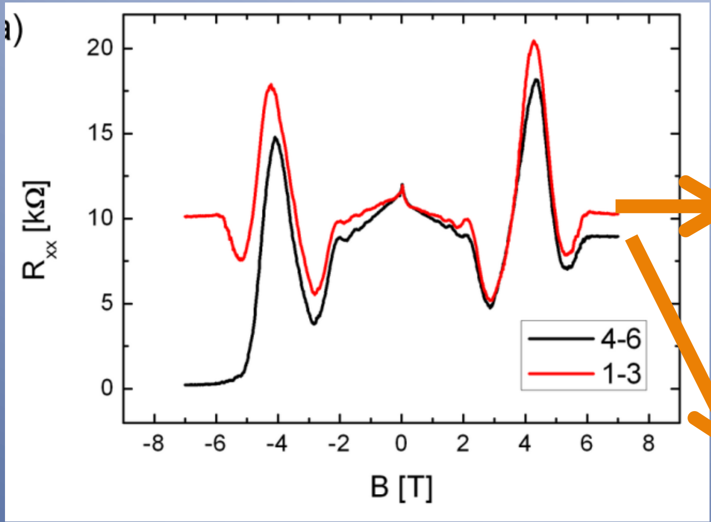


	R_{1-3}	R_{4-6}	R_{1-4}	R_{3-6}
B>0 (CW)	$\frac{\nu_B-\nu_M}{\nu_B\nu_M}$	$\frac{\nu_B-\nu_M}{\nu_B\nu_M}$	$\frac{1}{\nu_M}$	$\frac{1}{\nu_M}$
B<0 (CCW)	$\frac{\nu_B-\nu_M}{\nu_B\nu_M}$	0	$-\frac{1}{\nu_B}$	$-\frac{1}{\nu_M}$

in a unit of h/e^2

Quantitative approach

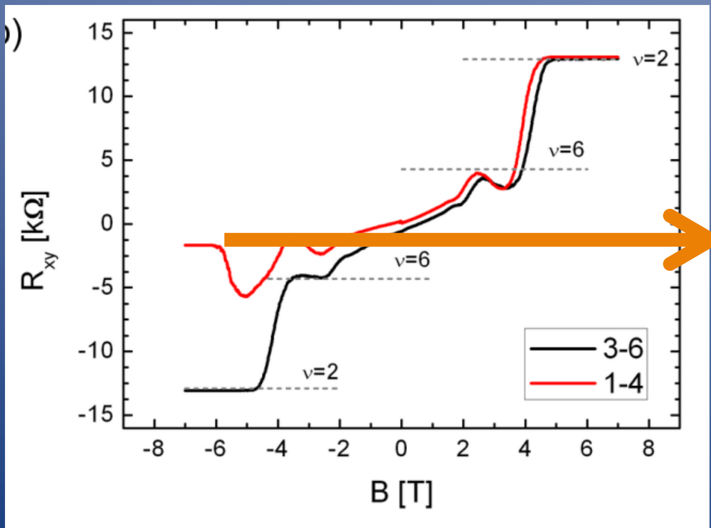




$$R_{1-3} = \frac{\nu_B - \nu_M}{\nu_B \nu_M} = 0.393 \times \frac{h}{e^2}, \quad \nu_M = 2$$

$$\rightarrow \nu_B = 9.3 \approx 8$$

$$\text{uncertainty } \Delta R_{XX} = 0.051 \times \frac{h}{e^2} \approx 1.3\ \text{k}\Omega$$



$$R_{1-4} = -\frac{1}{\nu_B} = -0.064 \times \frac{h}{e^2} \approx 1.65\ \text{k}\Omega$$

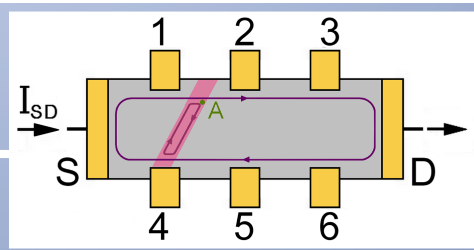
Using ν_B=8 → $R_{1-4} = -0.125 \times \frac{h}{e^2} \approx 3.23\ \text{k}\Omega$

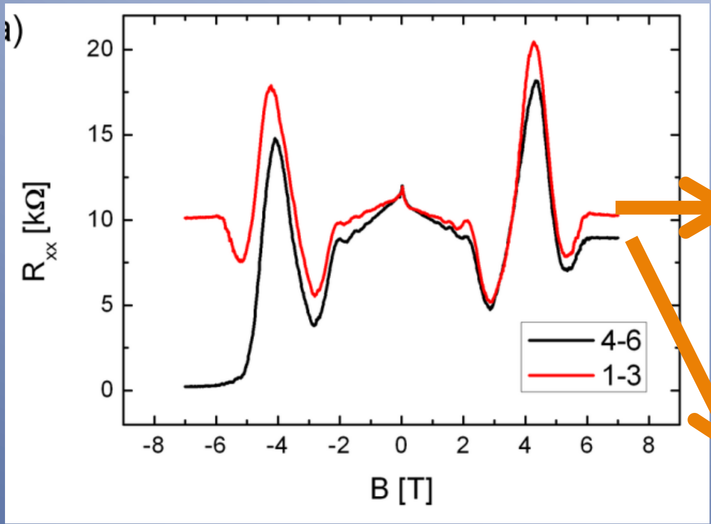
Summary

Hall bar oriented perpendicularly to the SiC(0001) step edges:

- We observe an **asymmetric B-dependence** of the magnetoresistance due to the continuous **bilayer stripe** crossing the device.
- We propose a **quantitative model** involving the simultaneous coexistence of quantum Hall conditions in the monolayer and bilayer regions, at **different filling factors**, which fully account for the asymmetry and the observed quantized resistance values.
- **The transport channels in the bilayer are responsible for mixing of the edge channels in the monolayer and deviations from the conventional quantum Hall effect.**

Quantitative approach





$$R_{1-3} = \frac{\nu_B - \nu_M}{\nu_B \nu_M} = 0.393 \times \frac{h}{e^2}, \quad \nu_M = 2$$

$$\nu_B = 9.3 \approx 8$$

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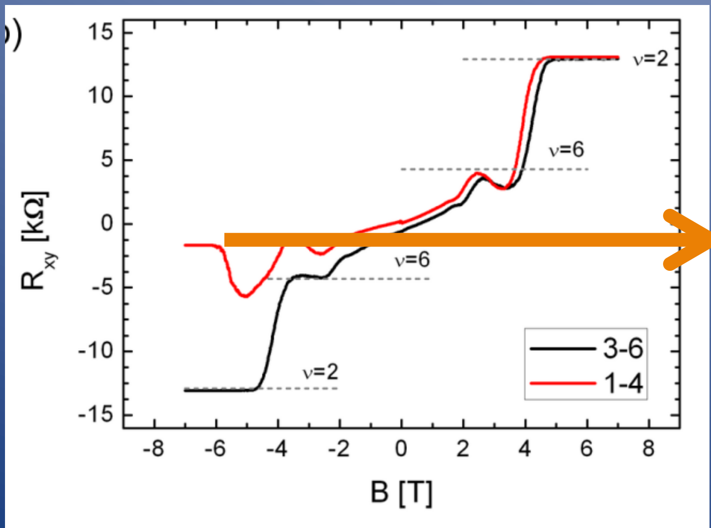

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Using ν_B=8

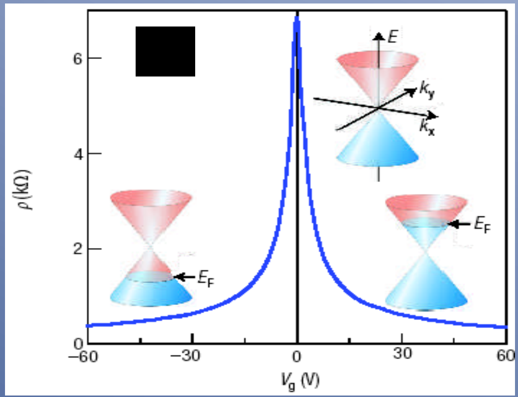
$$R_{1-4} = -0.125 \times \frac{h}{e^2}$$

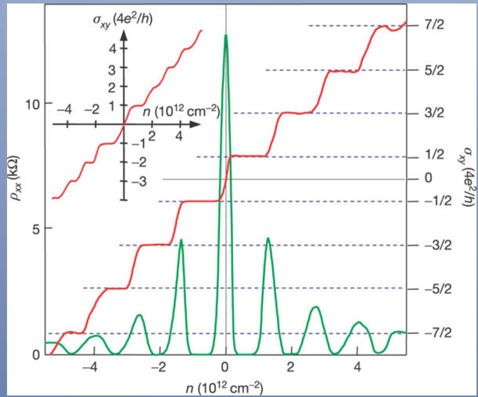
Motivation: Graphene

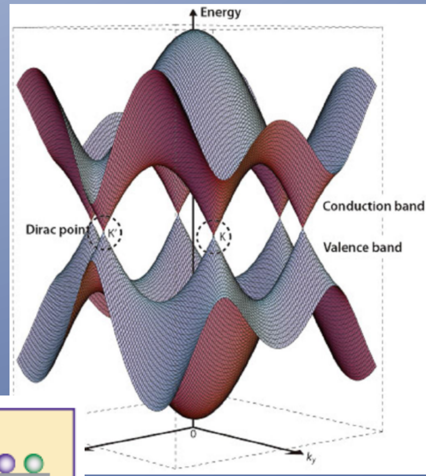
Why graphene?

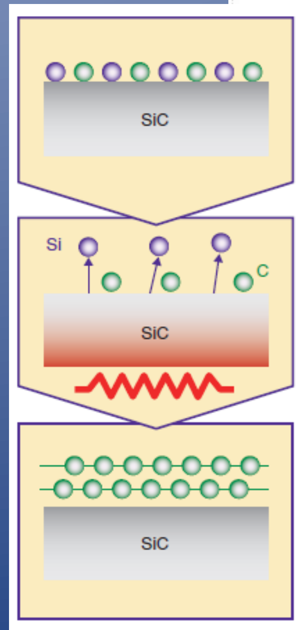
Unique Electronic Properties: Relativistic carriers, Klein tunneling, snake states…

Unique Conformational Properties: Single atom layer, exposed surface







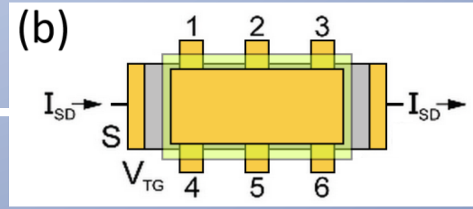


Ways to make graphene

- exfoliation from graphite (small)
- chemical vapor deposition (large, conductive substrate)
- epitaxial growth on SiC (large, wide-gap substrate)

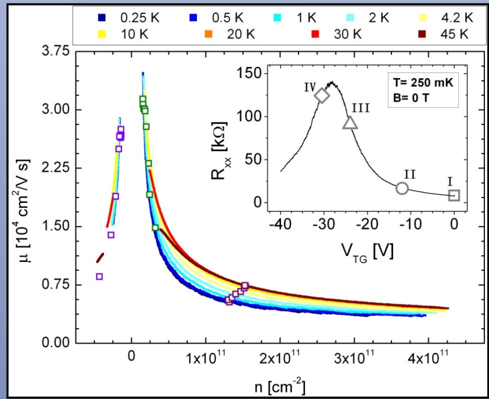
A. K. Geim and K. S. Novoselov, Nature Mater. 6, 183 (2007)
K. S. Novoselov et al., Nature 438, 197 (2005)
Y. Zhang et al., Nature 438, 201 (2005)
Hiroki Hibino et al., NTT Technical Review 8,(2010)

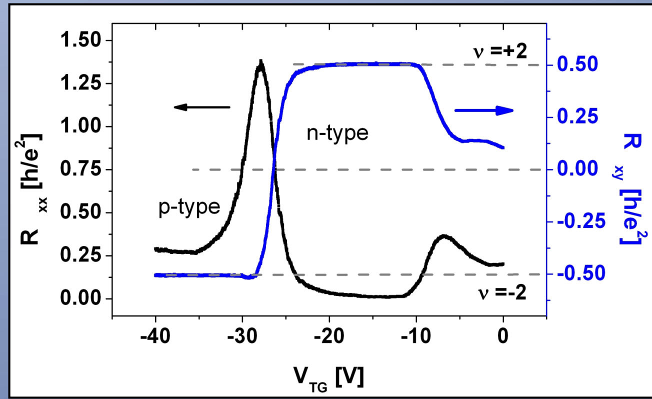
Device for low magnetic field



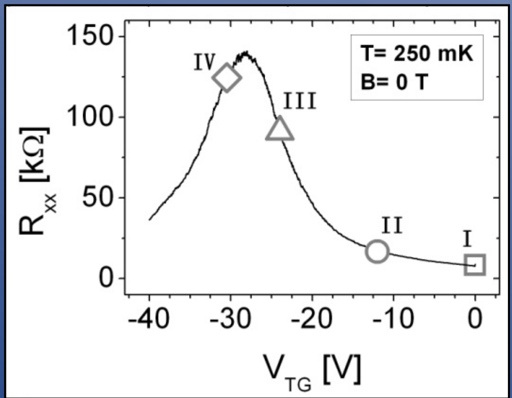
Tunable carrier density (and mobility)
n = -2×10^{10} to 4×10^{11} cm^{-2}
μ = 0 – 35000 cm^2/Vs

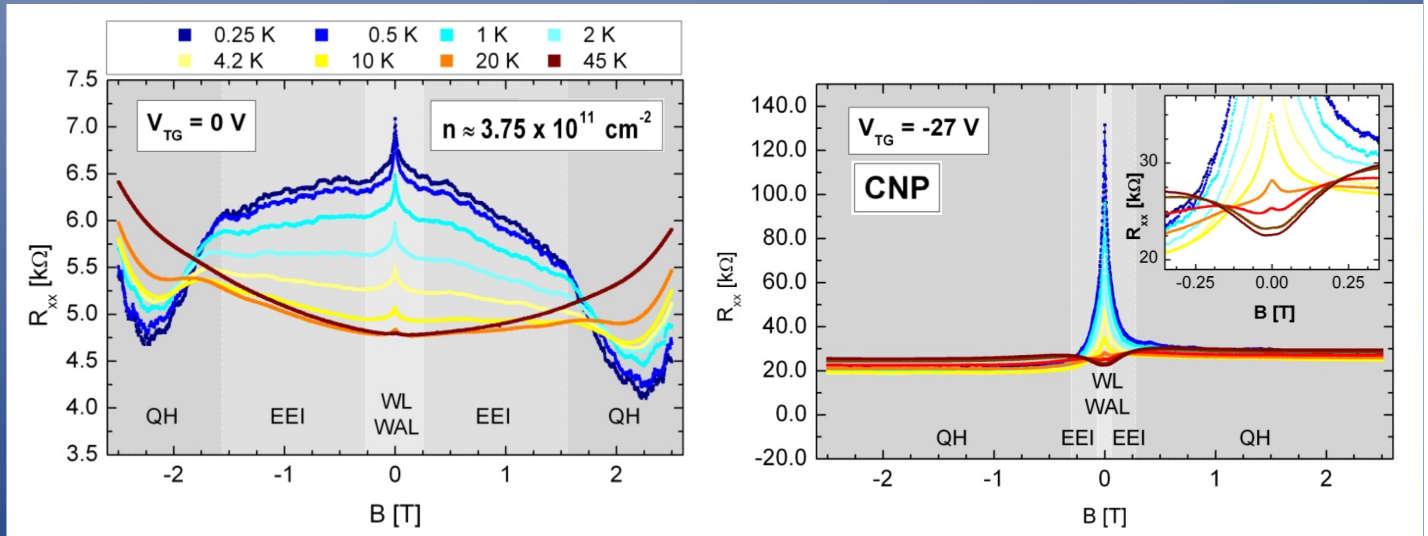
Monolayer graphene
(i.e., half-integer quantum Hall effect)





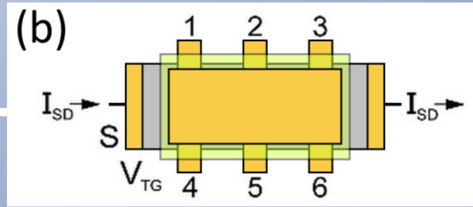
Dominant effect depends on carrier density





A. Iagallo, S. Tanabe, S. Roddaro, M. Takamura, H. Hibino, and S. Heun, Phys. Rev. B 88, 235406 (2013)

Electron-Electron interaction/01



$$\frac{\Delta R_{xx}}{R_0^2} \approx \left[(\omega_c \tau_0)^2 - 1\right] \frac{e^2}{2\pi^2\hbar} \left[K_{ee} ln\left(\frac{k_B T \tau_0}{\hbar}\right)\right]$$

$$\omega_C = \left(v_F e / \hbar\sqrt{\pi n}\right) B$$

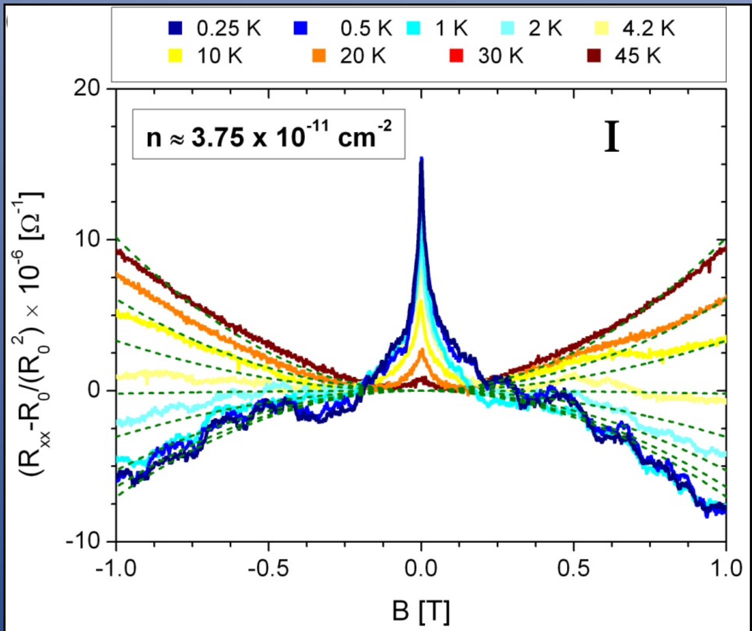
Quadratic magnetoresistance

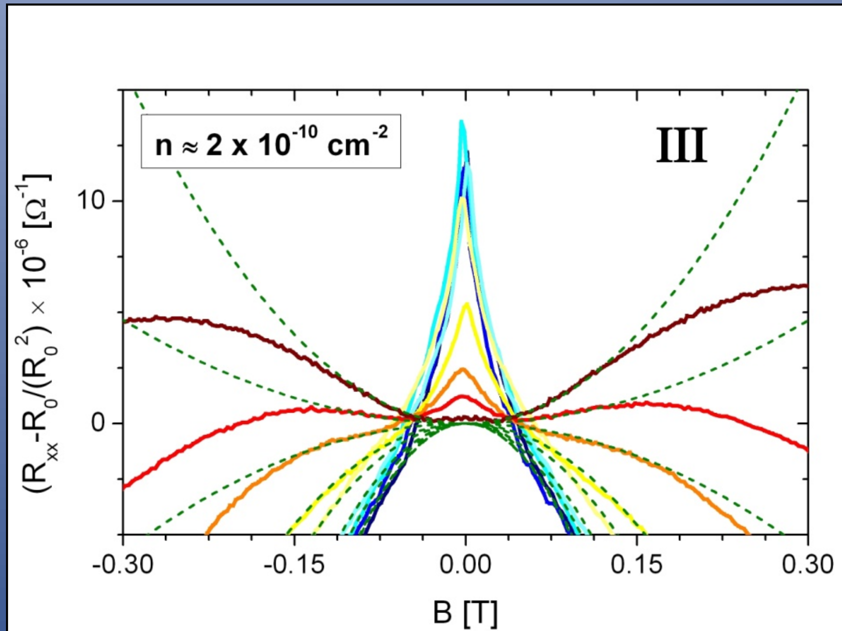
$$A = K_{ee} \ln\left(k_B T \tau_0 / \hbar\right) \text{ (curvature)}$$

K_{ee}: (adimensional) strength of interaction

~ln(T) (Fermi liquid)

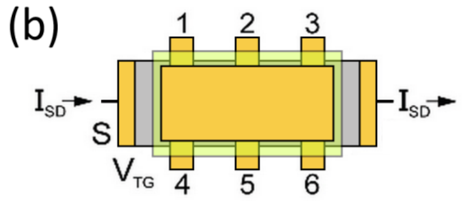
A. A. Kozikov et al., Phys. Rev. B 82, 075424 (2010).
J. Jobst et al., Phys. Rev. Lett. 108, 106601 (2012).
S. Lara-Avila et al., Phys. Rev. Lett. 107, 166602 (2011)





A. Iagallo, S. Tanabe, S. Roddaro, M. Takamura, H. Hibino, and S. Heun, Phys. Rev. B 88, 235406 (2013)

Electron-Electron interaction/02



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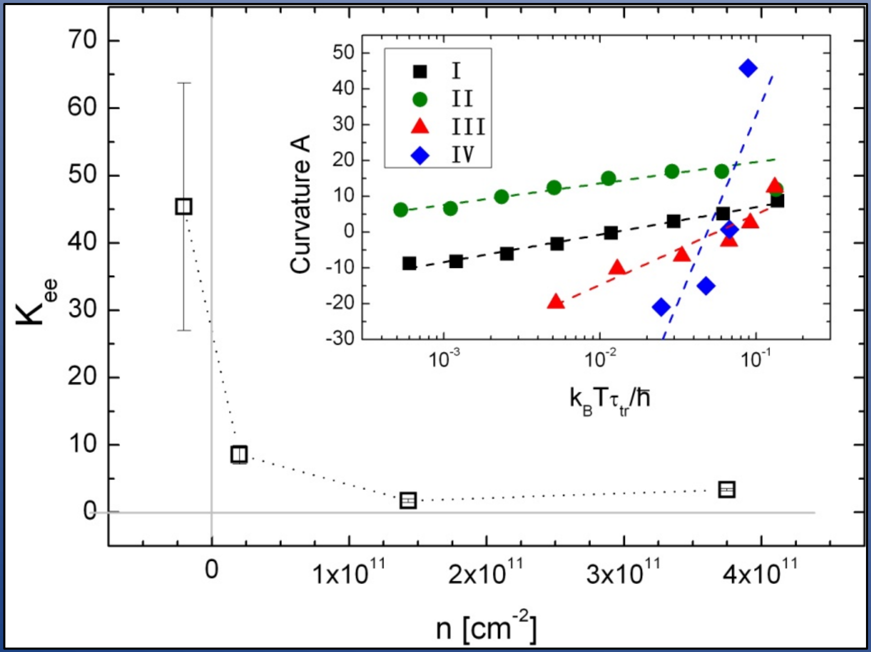
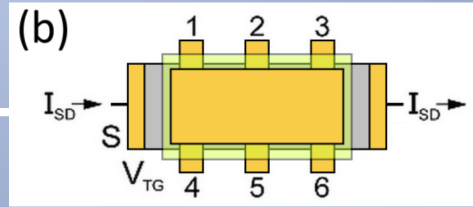


1. Linear slope → Electrons in disordered graphene behaves as a **Fermi liquid**.
2. Clear **n-dependence of K_{ee}** at low density, not accounted for by present theory (dielectric environment? charge inhomogeneity around CNP?)

A. Iagallo, S. Tanabe, S. Roddaro, M. Takamura, H. Hibino, and S. Heun, Phys. Rev. B 88, 235406 (2013)

Quantum Interference/01



After subtracting EEI contribution

$$\frac{\Delta R_{xx}}{R_0^2} = -\frac{e^2}{\pi h}\left[F\left(\frac{\tau_B^{-1}}{\tau_\varphi^{-1}}\right) - F\left(\frac{\tau_B^{-1}}{\tau_\varphi^{-1}+2\tau_{iv}^{-1}}\right) - 2F\left(\frac{\tau_B^{-1}}{\tau_\varphi^{-1}+\tau_*^{-1}}\right)\right]$$

E. McCann et al., Phys. Rev. Lett. 97, 146805 (2006)

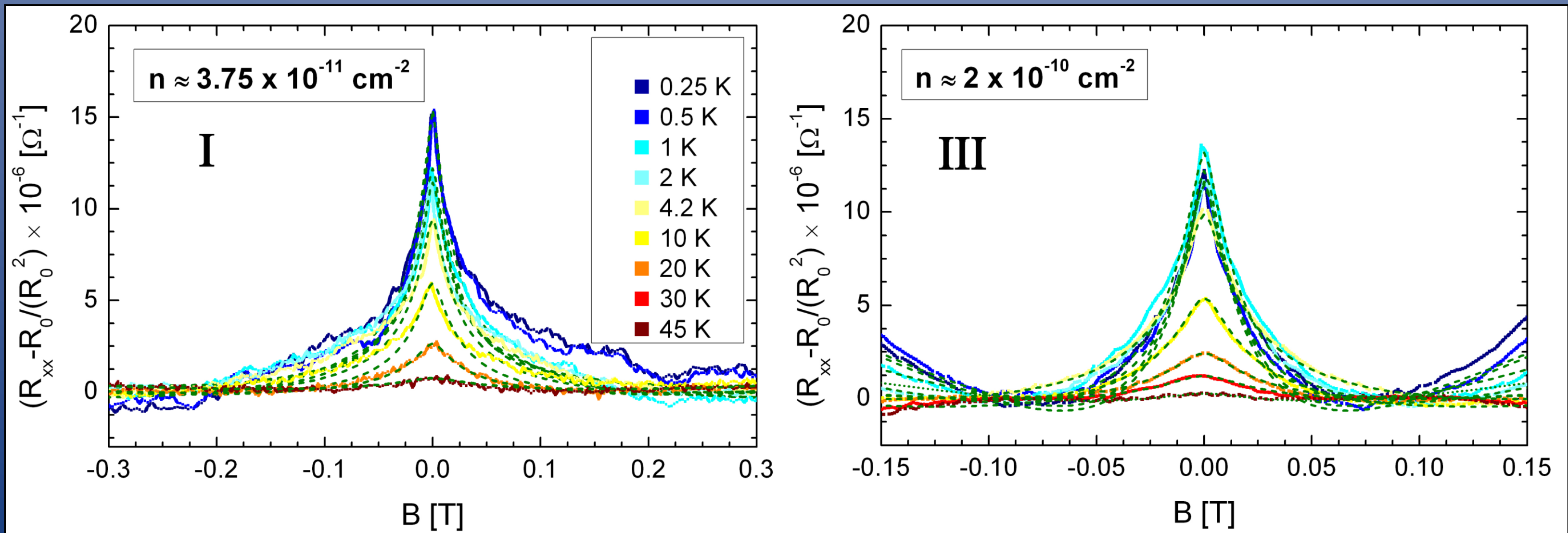
$F(z) = \ln(z) + \psi(0.5 + z^{-1}),\quad \psi(x)$ is the digamma fucntion

τ_φ = dephasing time

τ_{iv} = inter - valley scattering

τ_* = intra - valley scattering

$\tau_B^{-1} = \frac{4DeB}{\hbar}$, D = diffusion coefficient



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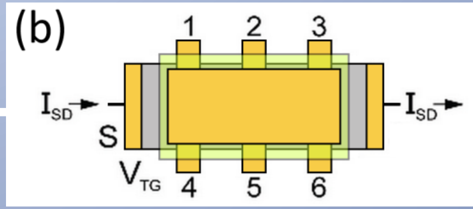
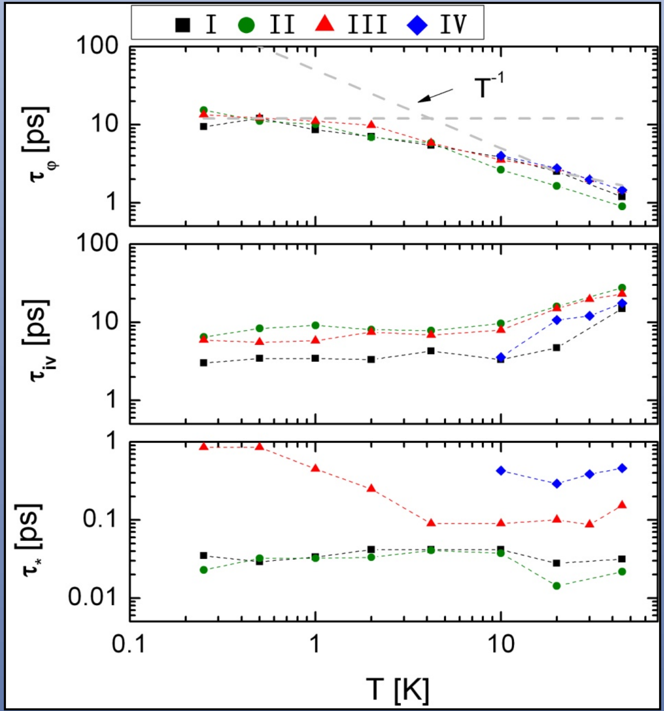
Quantum Interference/02



Dephasing time τ_φ:
Saturation in T;
Constant in n.

Intervalley scattering time τ_{iv} :
Almost constant in T;
Small variation with n.

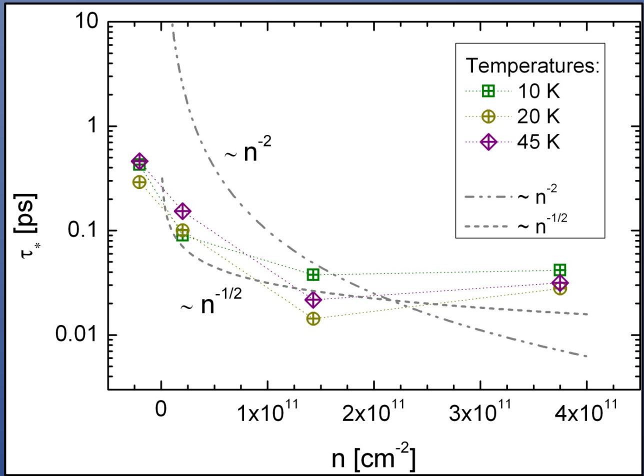
Intravalley scattering time τ_*:
Small variation in T;
Large variation with n.



<u>**τ_*: unexpected density dependence**</u>

trigonal warping gives ~ n^{-2}

The observed dependence is larger than the sole trigonal warping



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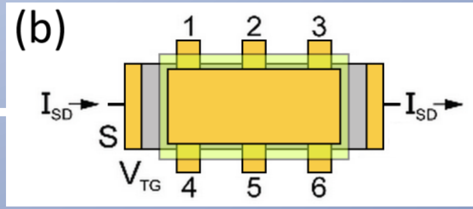
Low magnetic field summary



- We presented a **systematic** analysis of magnetotransport properties in epitaxial graphene grown on the Si-terminated face of SiC.
- We describe **EEI** in graphene with the current theory for disordered systems, and we find an **unexpected dependence of the interaction parameter K_{ee} on carrier density**.
- Fitting the **quantum interference** correction, we find that the dephasing and intervalley times are almost constant, while the **intravalley scattering time shows a peculiar dependence on density**, different from the sole warping term.
- Our results stress the **role of charge density** in determining quantum interference and EEI, and the necessity of further investigation of its impact **on the low-field magnetoresistance** of graphene devices.

A. Iagallo, S. Tanabe, S. Roddaro, M. Takamura, H. Hibino, and S. Heun, Phys. Rev. B 88, 235406 (2013)

Thank you for your attention

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