Bilayer-induced asymmetric quantum Hall effect in epitaxial graphene

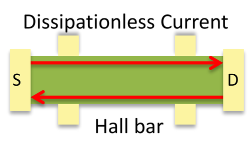
A. Iagallo,[1] S. Tanabe,[2] S. Roddaro,[1] M. Takamura,[2] Y. Sekine,[2] H. Hibino,[2] V. Miseikis,[3] C. Coletti,[3] V. Piazza,[3] F. Beltram,[1,3] and S. Heun[1]

[1] NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy
[2] NTT Basic Research Laboratories, NTT Corporation, Atsugi, Kanagawa, Japan
[3] Center for Nanotechnology Innovation @ NEST, Istituto Italiano di Tecnologia, Pisa, Italy

Introduction

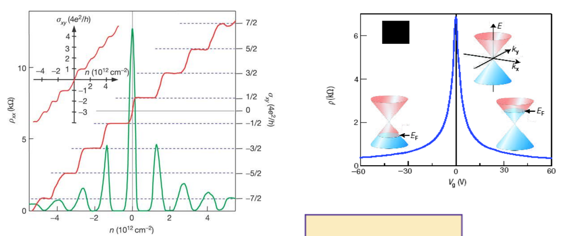
The quantum Hall effect

Dissipationless current
Edge current flows in quantum Hall regime
Controlling dissipationless current → future low-energy consumption devices

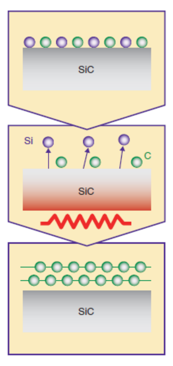


Why graphene?

- Clear quantum Hall effect is observed
- High mobility
- Filling factor differs between mono- and bilayer graphenes
- New ideal material for QH metrology



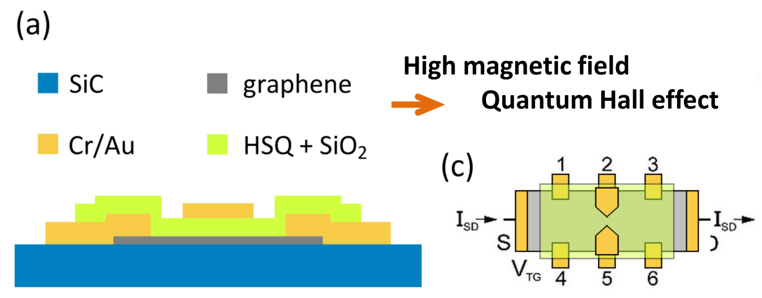
Graphene on SiC
Epitaxial growth by Si sublimation technique
large area, high quality, insulating substrate



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)

Fabrication: Side-Gated Devices

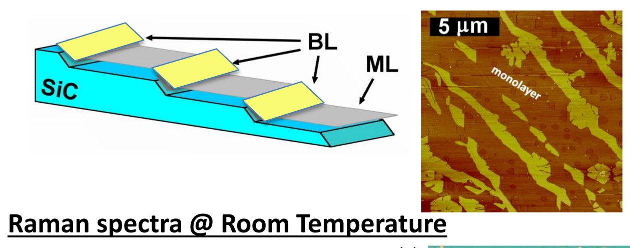
- Epitaxial graphene grown on the Si face of SiC (0001).
- Large area Hall bars (300 μm x 50 μm)
- Ohmic contacts: Cr/Au (5/250 nm)
- Gate insulator: HSQ (Hydrogen Silsequioxane) (140 nm) + SiO_2 (40 nm)
- Split-gate: Cr/Au (10/30 nm)

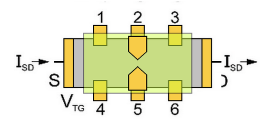


S. Tanabe, Y. Sekine, H. Kageshima, M. Nagase, and H. Hibino, Phys. Rev. B 84, 115458 (2011).

First Step
Characterization of the electric properties of the device without applying side-gate voltage

Sample: AFM & Raman





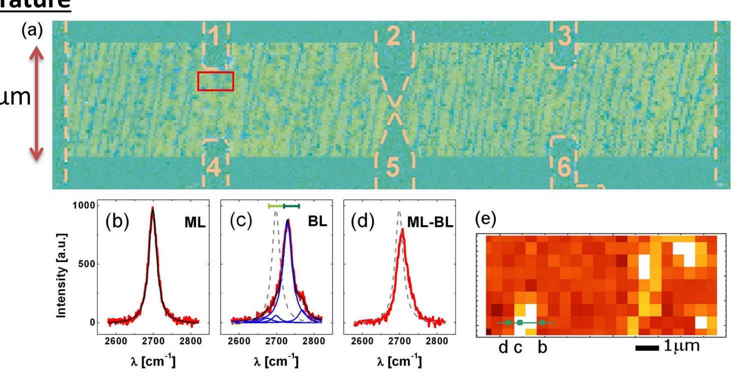
~ few μm wide monolayer regions on SiC terraces

≤1 μm wide bilayer domains along step edges

Raman spectra @ Room Temperature

(Renishaw Micro-Raman)
532 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}



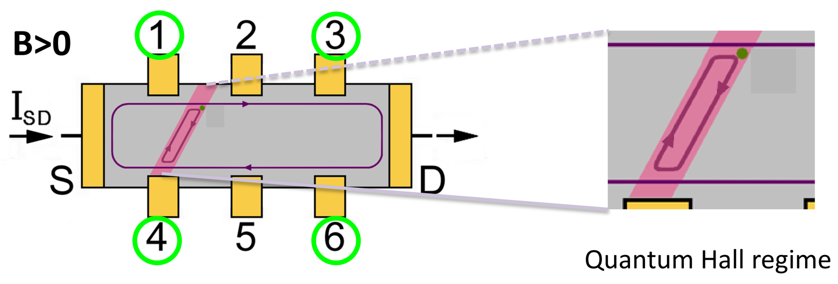
The Hall bar is intersected by tens of SiC step edges, onto which elongated bilayer domains are present.

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

Results

Configuration of mono- and bilayers

Bilayer stripe (red) crossing Hall bar



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

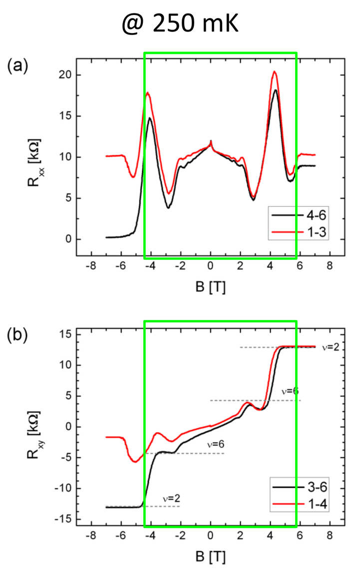
transverse resistance R_{xy}: $R_{1\text{-}4}$, $R_{3\text{-}6}$

Filling factor
Monolayer graphene
$\nu_M = \pm 2(2n+1)$ n = 0, 1, 2, ···

Bilayer graphene
$\nu_B = \pm 4n$ n = 1, 2, 3, ···

Magnetoresistance (1): Low Magnetic Field

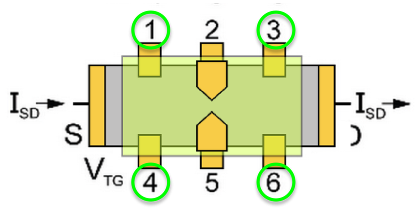
@ 250 mK



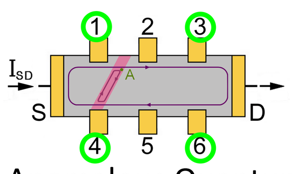
|B| < 5 T Conventional quantum Hall effect of monolayer graphene

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.

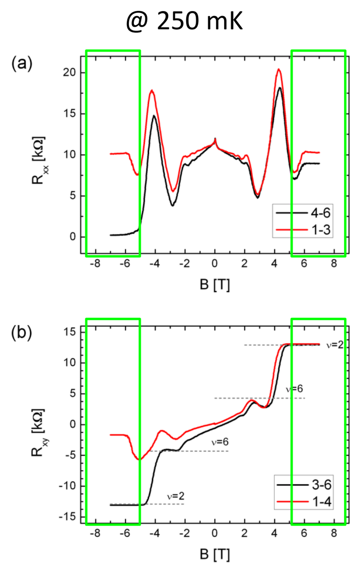


Magnetoresistance (2): High Magnetic Field



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

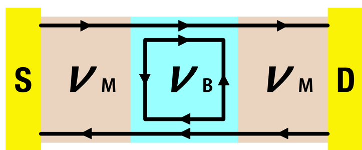
→

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

Discussion

Landauer-Büttiker:

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

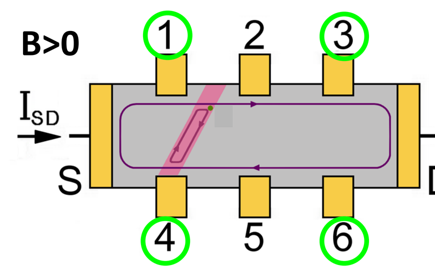


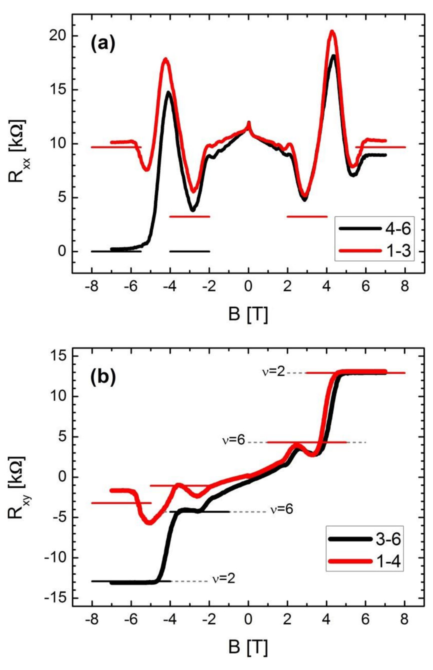
$|\nu_B| > |\nu_M|$, $\nu_B \cdot \nu_M > 0$

- Mixing of channels
- Current conservation at boundaries between mono- and bilayer graphene

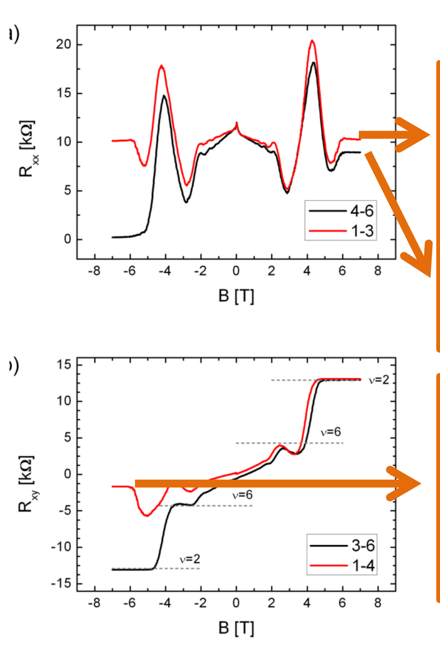
$I_S = I$, $I_D = -I$, $I_i = 0$
I_i : current
r_{ii} : total reflection coefficient at electrode i
(r_{ii} = 0 for ideal lead)
μ_i : electrochemical potential
T_{ij} : total transmission coefficient from i to j electrodes
(probability ejected into ν proportional to $1/\nu$ for each electron)

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





in units of h/e^2



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

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

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

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

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.**

Funding

Ministero degli Affari Esteri e della Cooperazione Internazionale
Consiglio Nazionale delle Ricerche
Japan Society for the Promotion of Science 日本学術振興会
GRAPHENE FLAGSHIP

For more details, see A. Iagallo *et al.*: Semicond. Sci. Technol. **30**, 055007 (2015).