Plateau-Insulator transition in graphene

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D.K. Maude LNCMI Grenoble

Outline

- Brief Introduction. What is graphene?
- Honeycomb lattice: Singular properties of graphene
- Sample processing
- QHE and QHE in graphene.
- Experimental set-up.
- Hall measurements and Plateau-Insulator transition.
- Conclusions and future work.

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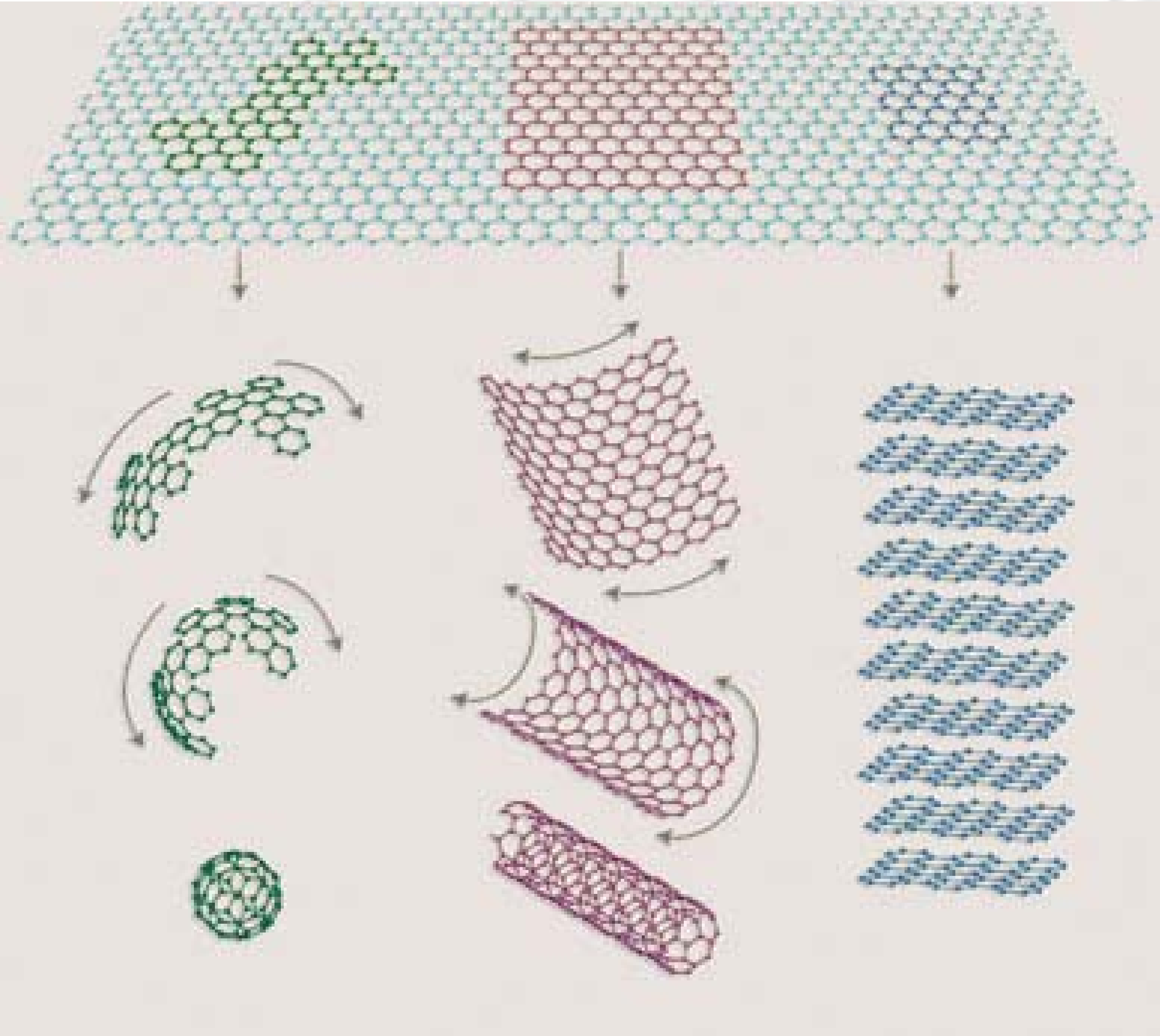
From graphite to graphene



0D 1D 2D

P.R. Wallace Phys. Rev. **71**, 622 - 634 (1947)

From graphite to graphene

Graphene was said not to exist in the free state….

….but many works studied the system:

- Continuum approximation to fullerene molecules

J. González, F. Guinea, and M. A. H. Vozmediano Phys. Rev. Lett. **69**, 172 (1992)

- Electronic structure of single- and multiple-shell carbon fullerenes

Yeong-Lieh Lin and F. Nori Phys. Rev. B **49,** 5020 (1994)

- Zero modes for Dirac fermions on a sphere with fractional vortex

V. A. Osipov, E. A. Kochetov J. of Exp. and Th. Phys. Lett. **72** 199 (2000)ok

- Electron-electron interactions in graphene sheets

J. González, F. Guinea, and M. A. Vozmediano Phys. Rev. B **63** 134421 (2001)

- Graphene cones: Classification by fictitious flux and electronic properties

P. E. Lammert and V. H. Crespi Phys. Rev. B **69** 035406 (2004)

The rise of graphene

Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1*] S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

We describe monocrystalline graphitic films, which are a few atoms thick but are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films are found to be a two-dimensional semimetal with a tiny overlap between valence and conductance bands, and they exhibit a strong ambipolar electric field effect such that electrons and holes in concentrations up to 10^{13} per square centimeter and with room-temperature mobilities of ~10,000 square centimeters per volt-second can be induced by applying gate voltage.

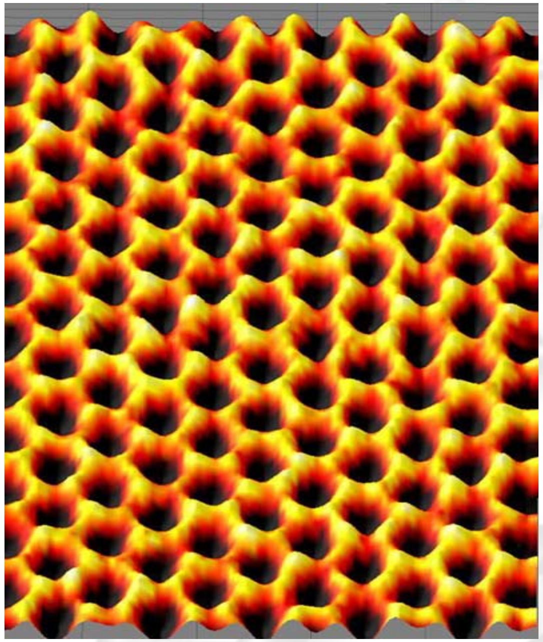
Science **306**, 666 (2004)

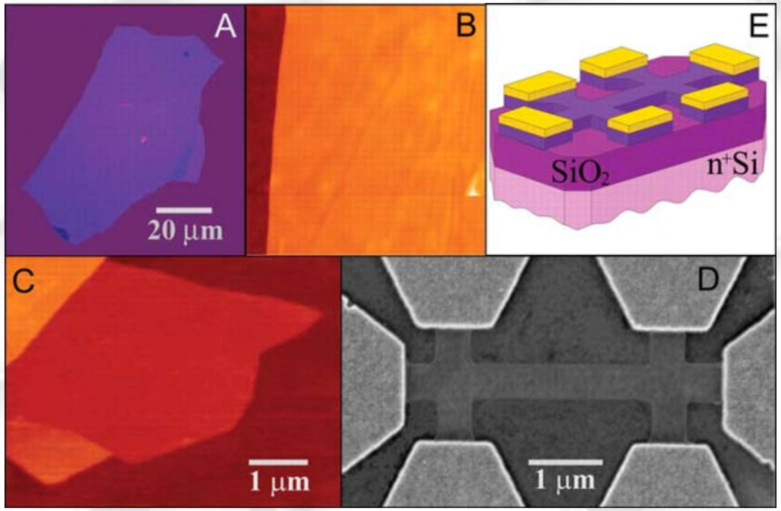
Two-dimensional gas of massless Dirac fermions in graphene

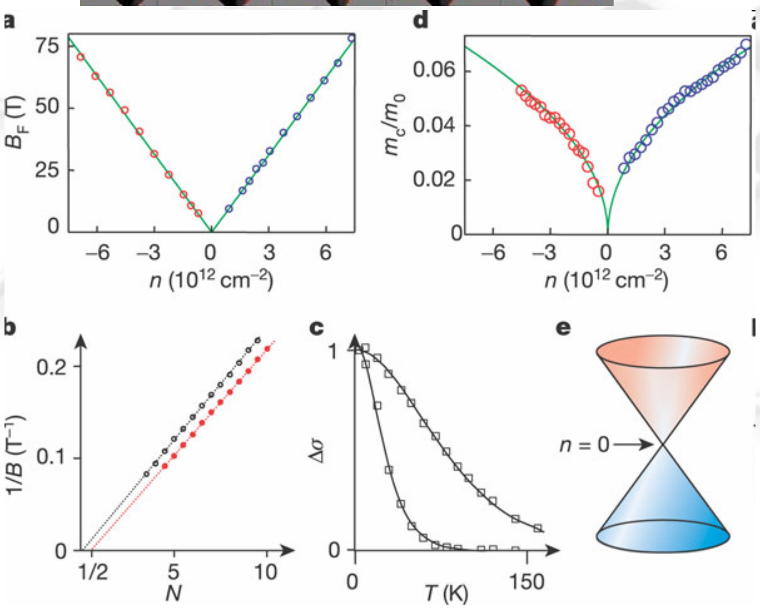
K. S. Novoselov[1], A. K. Geim[1], S. V. Morozov[2], D. Jiang[1], M. I. Katsnelson[3], I. V. Grigorieva[1], S. V. Dubonos[2] & A. A. Firsov[2]

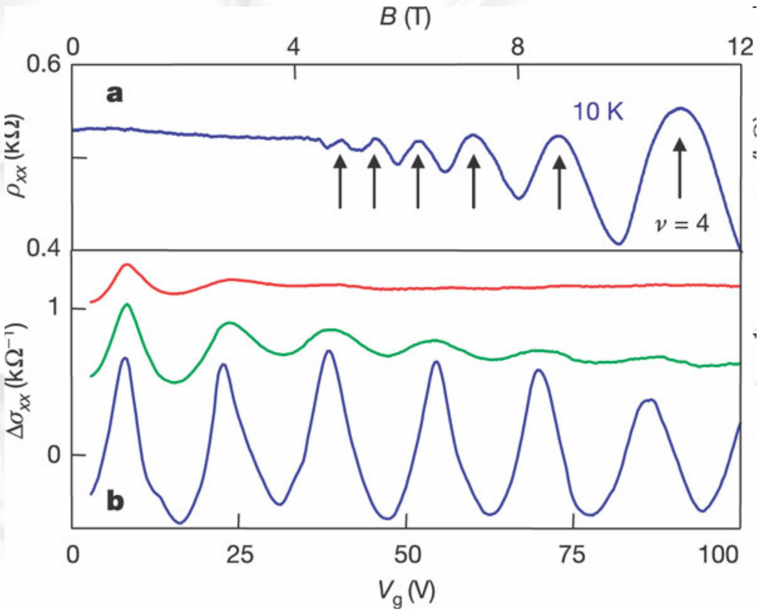
Nature **438**, 197-200 (2005)

Graphene: a true 2D system.









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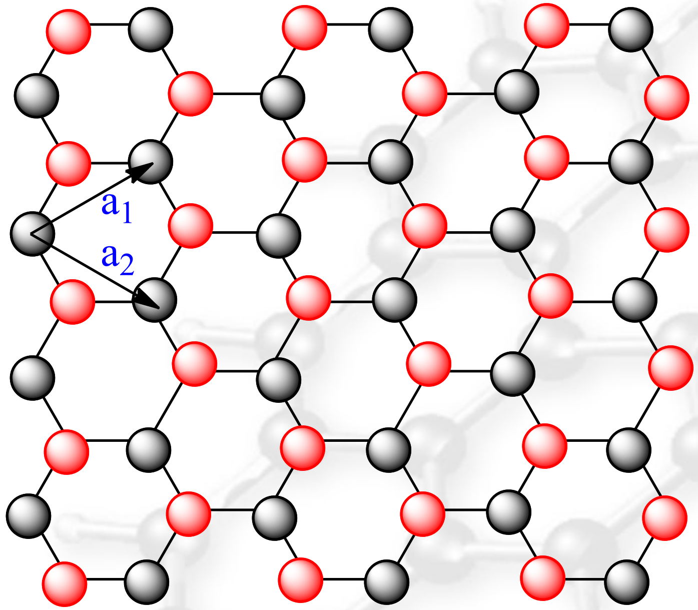
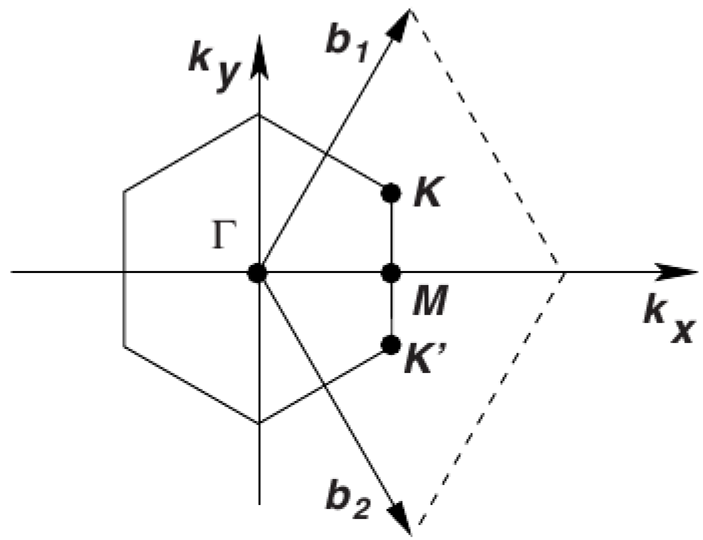
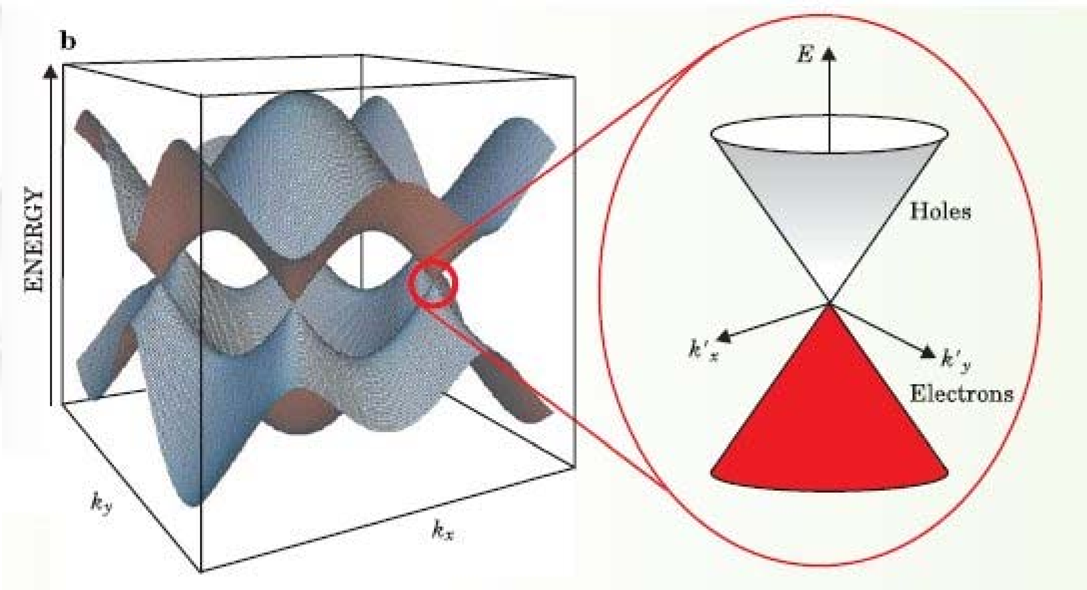
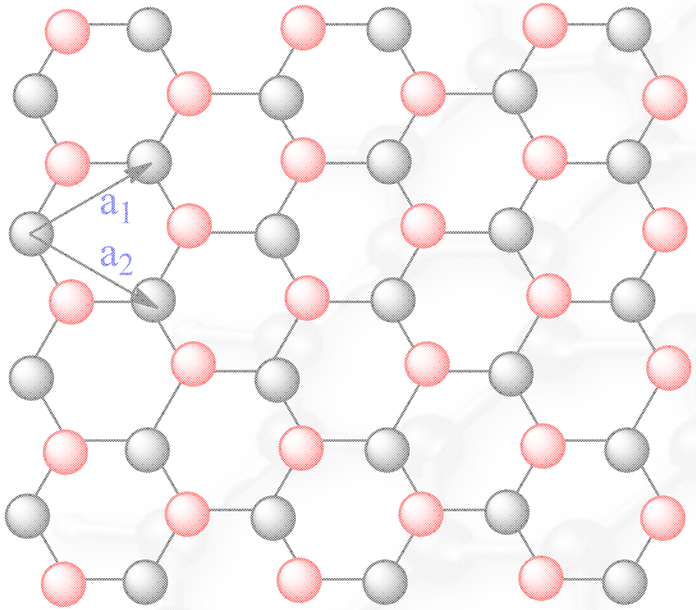
Brillouin's zone in graphene.

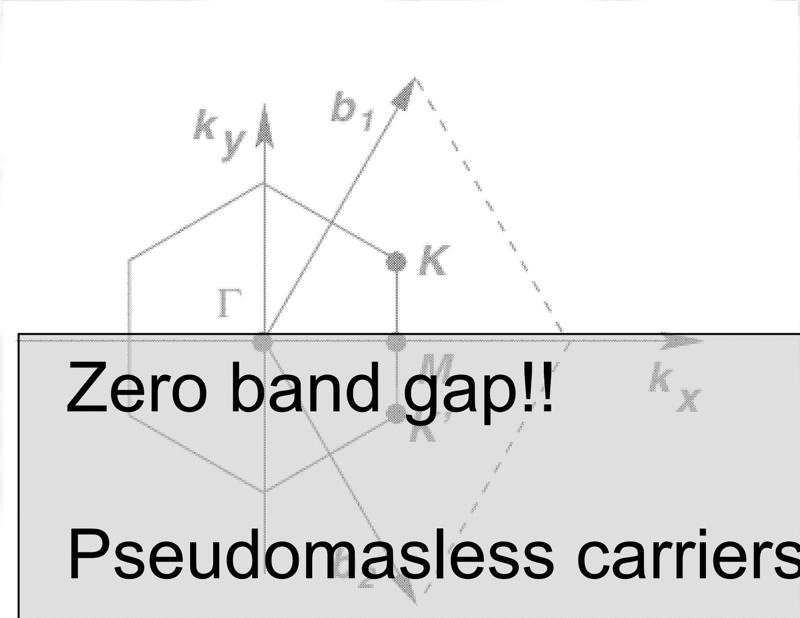






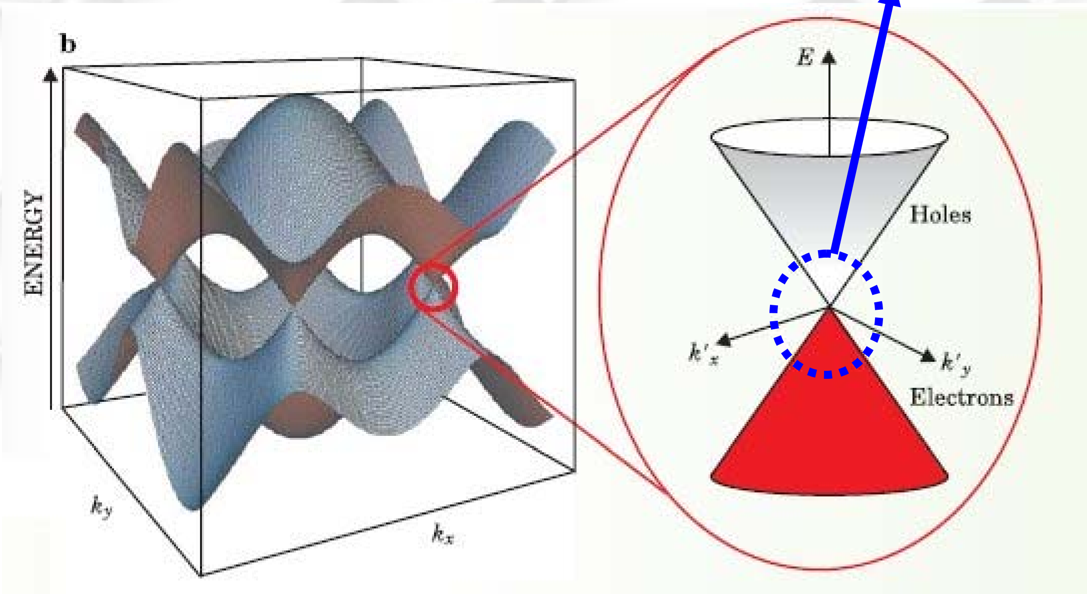
Brillouin's zone in graphene.





Zero band gap!!

Pseudomasless carriers!



Why graphene is so different?

Semiconductors

Open band-gap
Schrödinger-like equation in most of them
Degeneracy 2.
Conduction by electrons OR holes.

$$E = \frac{p^2}{2m}$$

Graphene

Zero band-gap → Semimetal
Dirac-like equation
Degeneracy 4.
Conduction by electrons AND holes

$$E = \hbar v |k|$$

$$v \sim c / 300$$

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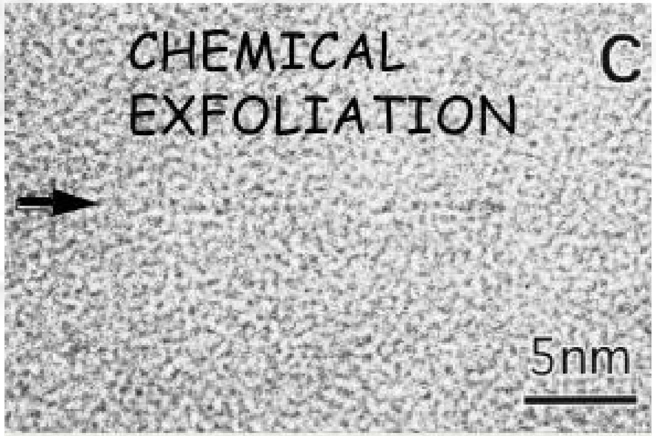
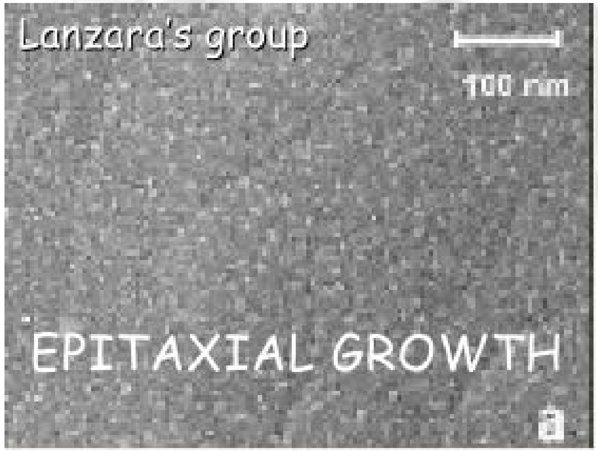
The rise of graphene. Previous approaches.

More than 80 layers
Krishnan'98



Dresselhaus '81
Horiuchi '04
Restacked and scrolled

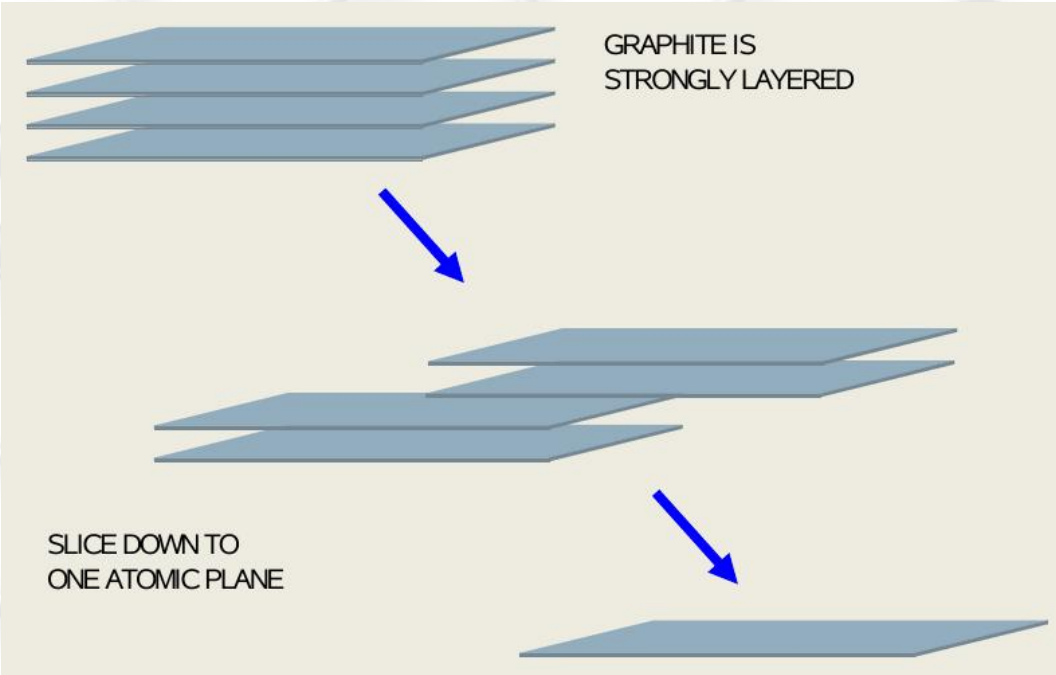


McConville '86
Land '92
Affoune '01
…
Submicron islands on top of a 3D crystal.

Graphite peeling. Mechanical exfoliation.

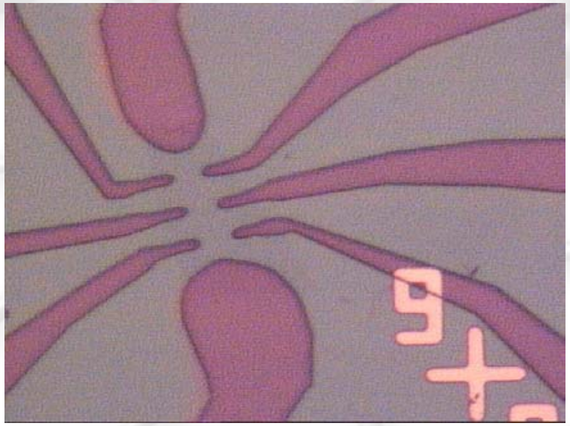
Sample processing.

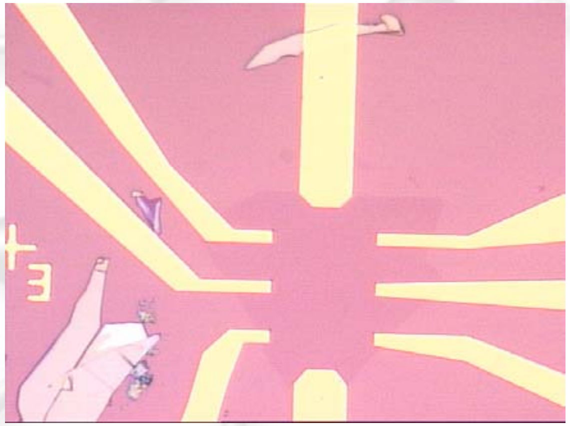
- Mechanical exfolation. It is dificult to obtain big and homogeneus flakes

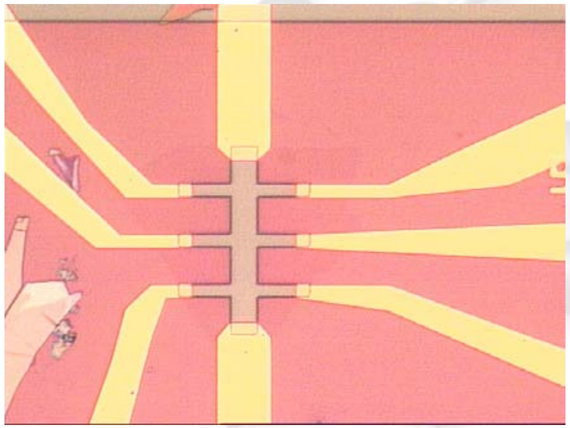


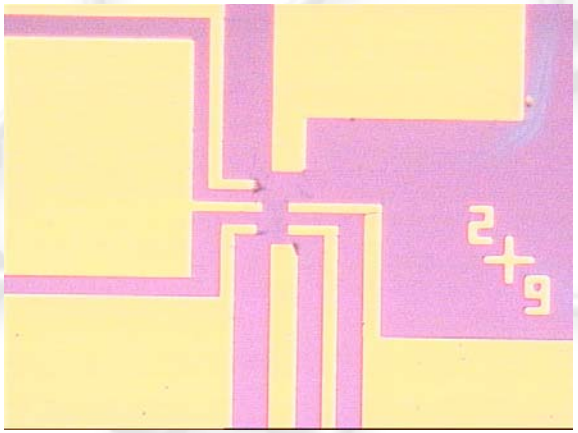
- Transfer to a 300 nm SiO_2/Si substrate. The Si is n-doped and is used as a gate.
- The substrate should be patterned with position markers

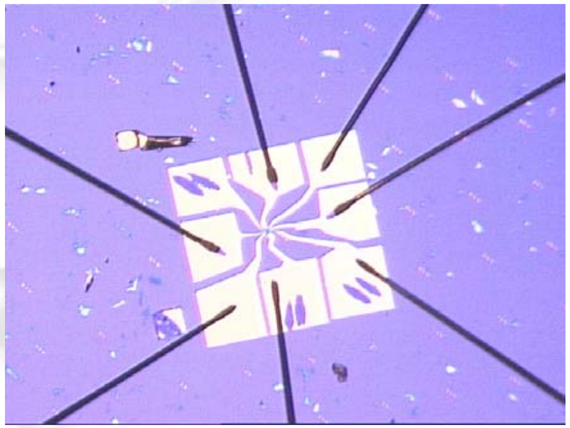
Sample processing











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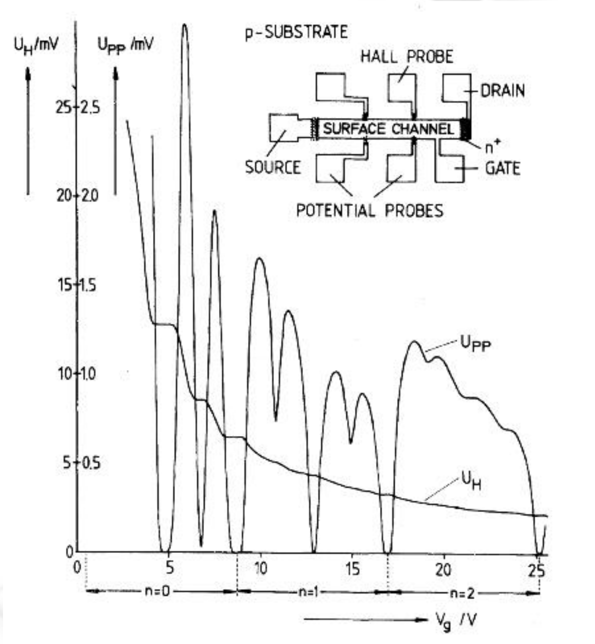
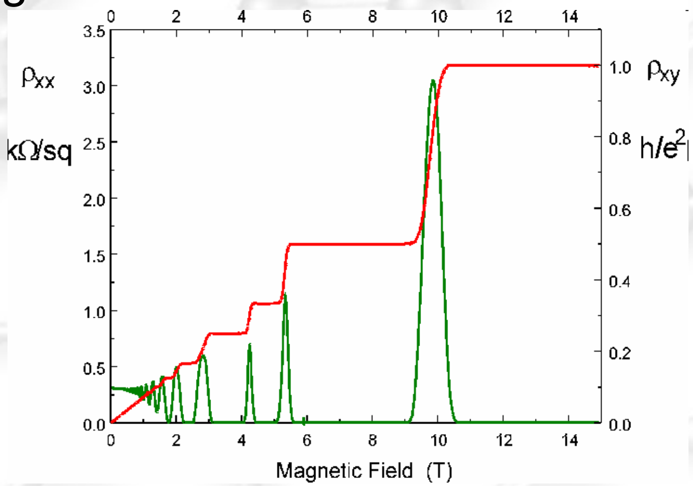
Quantum Hall Effect (QHE).

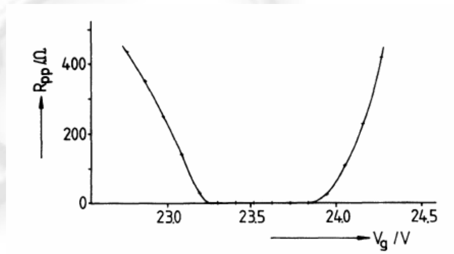
The non-diagonal element of the resistivity tensor is quantized: $\rho_{xy}=h/\nu e^2$ being ν the filling factor



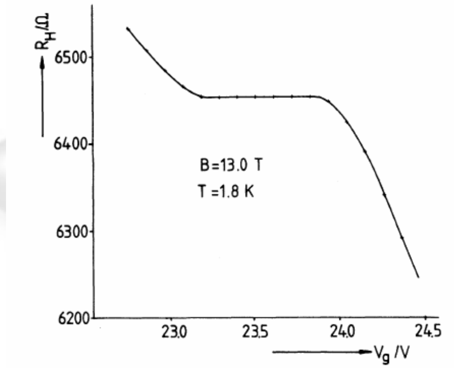
Electron density variation (V_g) for a fixed value of B

K. v. Klitzing, G. Dorda, M. Pepper, Phys. Rev. Lett. **45**, 494 (1980)



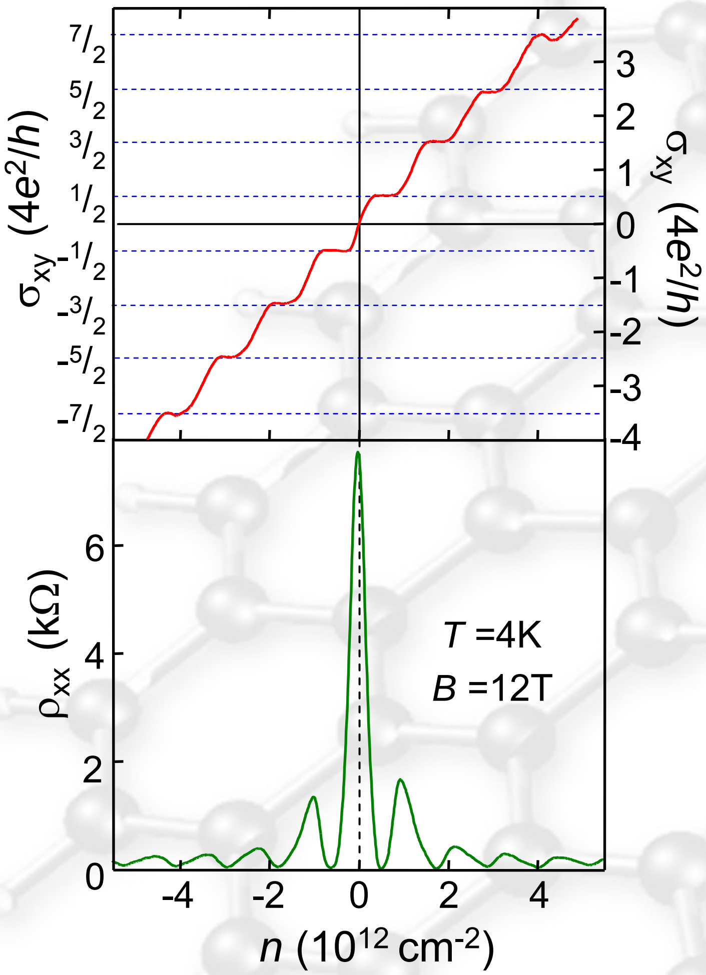


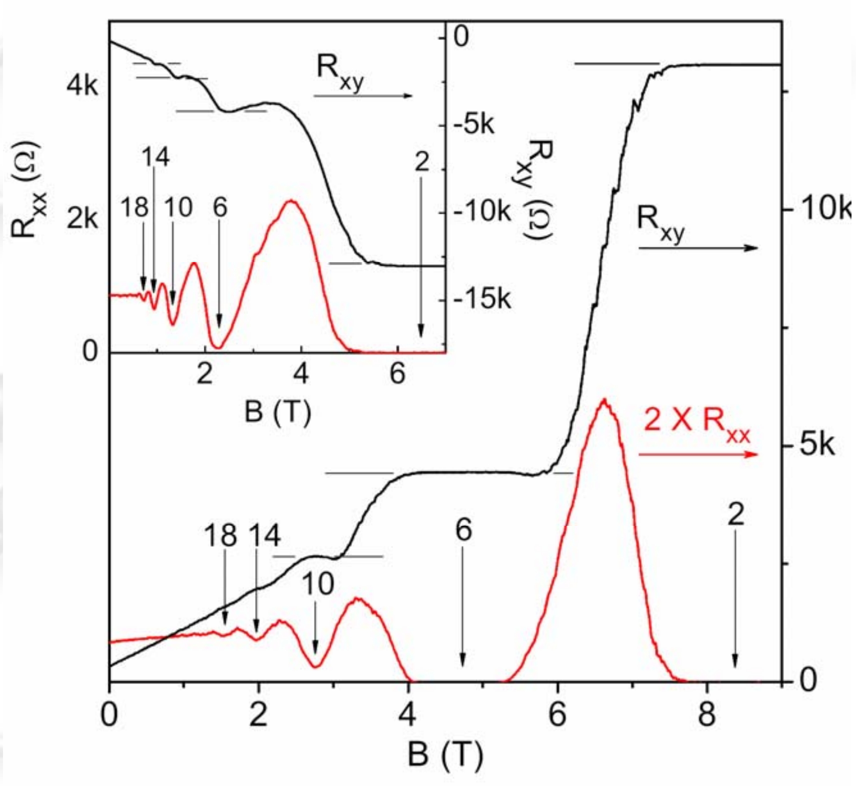
The longitudinal resistance drops to zero



Plateau: Hall resistance remains constant $R_H=h/e^2\,\nu$

Anomalous QHE in graphene.





Y.Zhang, Kim *et al.*, Nature **438**, 201 (05)

Novoselov, Geim *et al.*, Nature **438**, 197 (05)

Quantum Hall Effect (QHE).

2DEG in semiconductors
$$\begin{cases} E_n = \left(n + \dfrac{1}{2}\right)\hbar\omega_c \\ \sigma_{xy} = ne^2 / h \end{cases}$$

Graphene
$$\begin{cases} E_n = \pm\sqrt{2n\hbar v^2 \left|eB\right| / c} \\ \sigma_{xy} = \pm g_s g_v (n+1/2)e^2 / h = \pm 4(n+1/2)e^2 / h \end{cases}$$

$$n = 0,1,2,..$$

$$\omega_c = \frac{eB}{m}$$

$$g_s g_v = 4$$

Quantum Hall Effect (QHE).

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The shift 1/2 is originated from the Berry phase due to the pseudospin (or valley) precession when a massless (and thus chiral) Dirac particle exercises cyclotron motion.

Quantum Hall Effect (QHE).

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Graphene
$$\begin{cases} E_n = \pm\sqrt{2n\hbar v^2 |eB|/c} \\ \sigma \ldots \pm \ldots (n+1/2)e^2/h = \pm 4(n+1/2)e^2/h \end{cases}$$

,..

$\nu = \pm 4(n+1/2)$

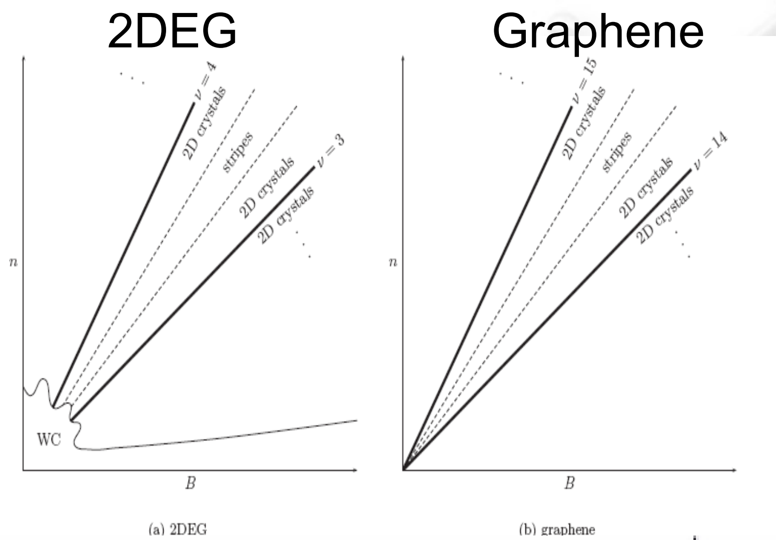
In the limit n→0, nothing happens to the LLs n≥1

The two n=0 LLs with $E=\pm mv^2$ merge together to form a single level with degeneracy 4. Is a partially filled LL !

R_{xy} in 1st LL is $2(h/e^2) = \frac{1}{2}R_K$

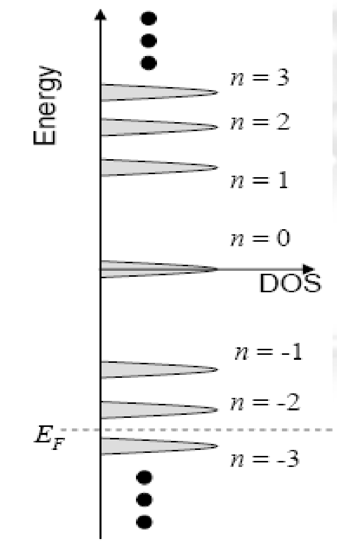
$$R_K = 25.812\ \mathrm{k\Omega}$$

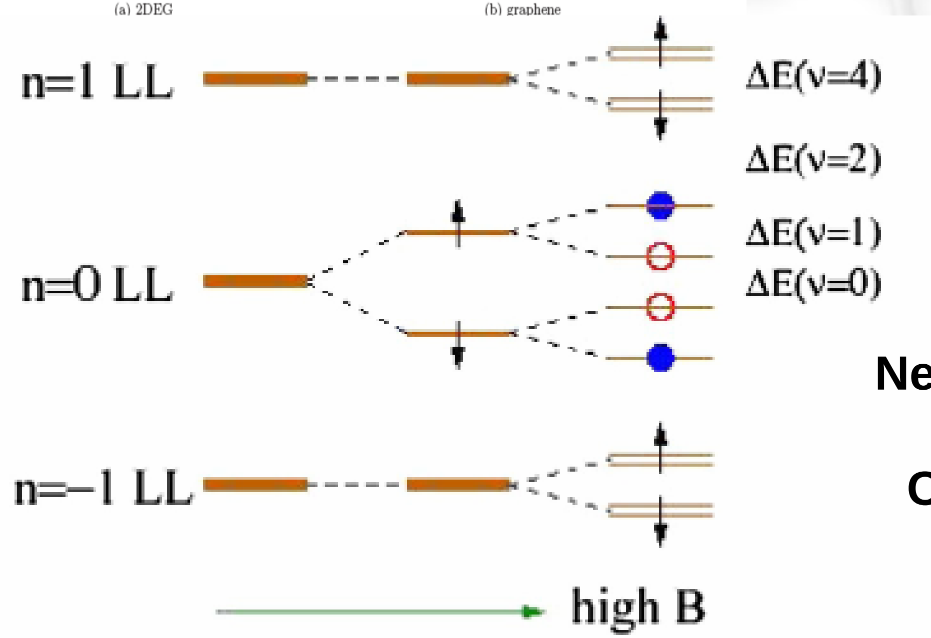
Quantum Hall Effect (QHE).



(a) 2DEG (b) graphene

Wang, Iyengar, Fertig and Brey
PRB **78** 165416 (2008)





Jiang, Zhang, Stormer and Kim
PRL **99**, 106802 (2007)

New Plateaus at High Magnetic Fields

Contradictory experimental results
In the extreme quantum limit!

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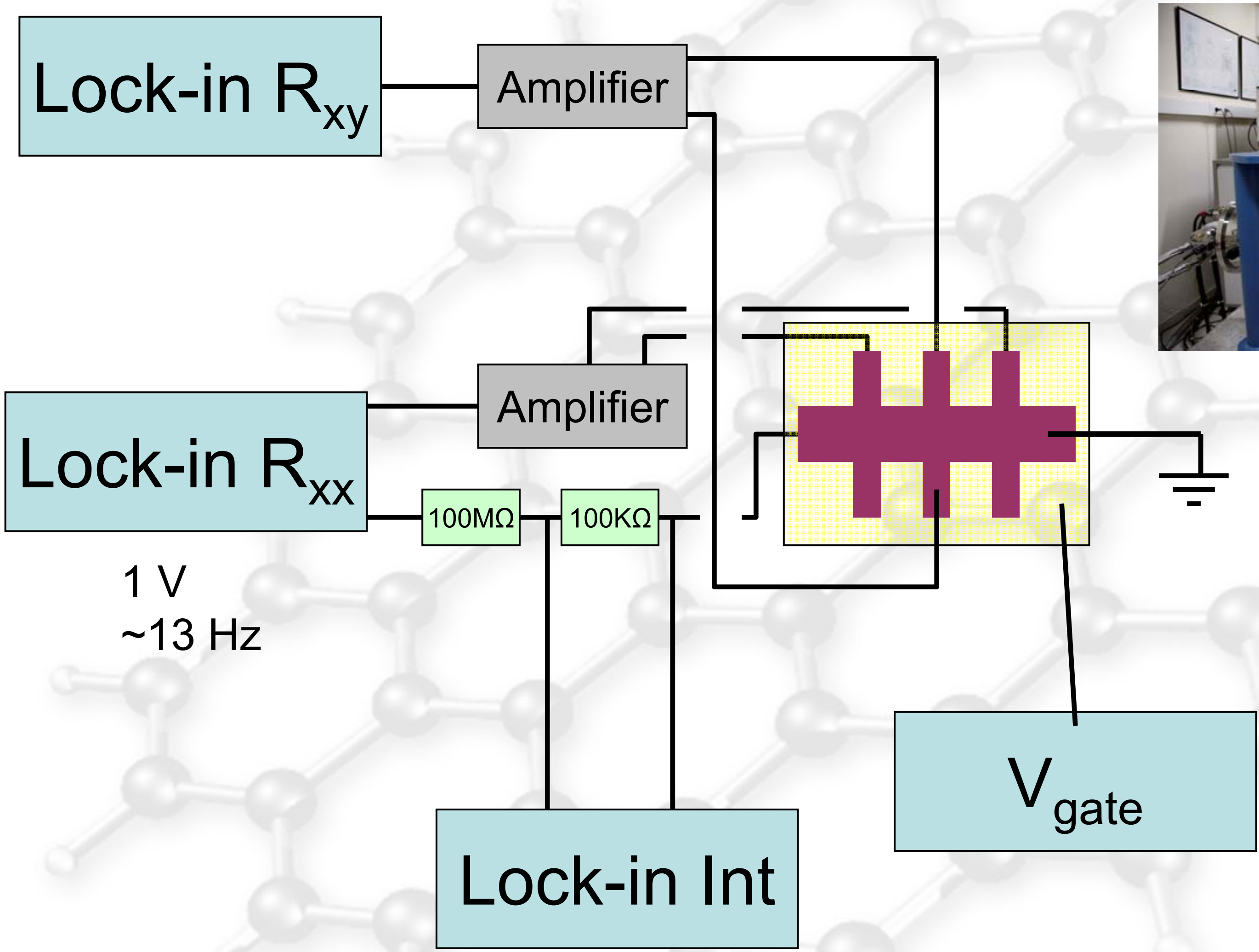
Experimental set-up.



300mK and 12T

1,4K and 28T

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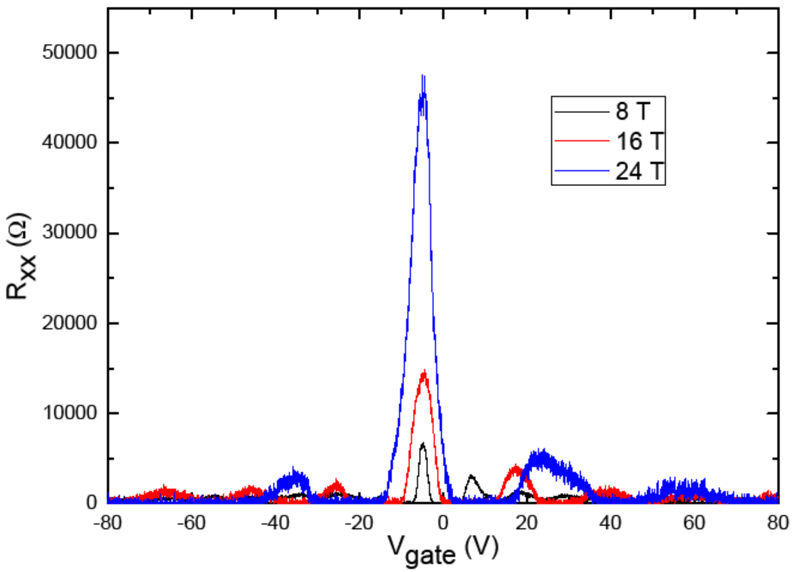
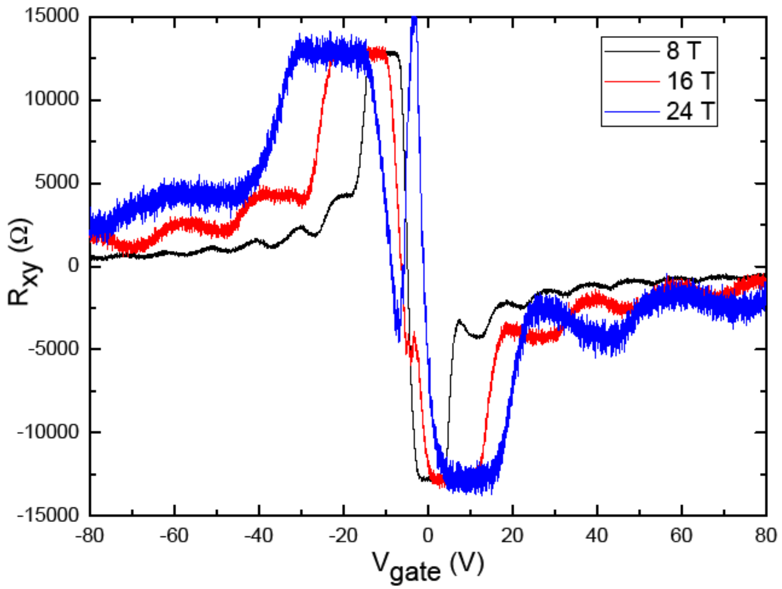
QHE by varying the V_{gate}

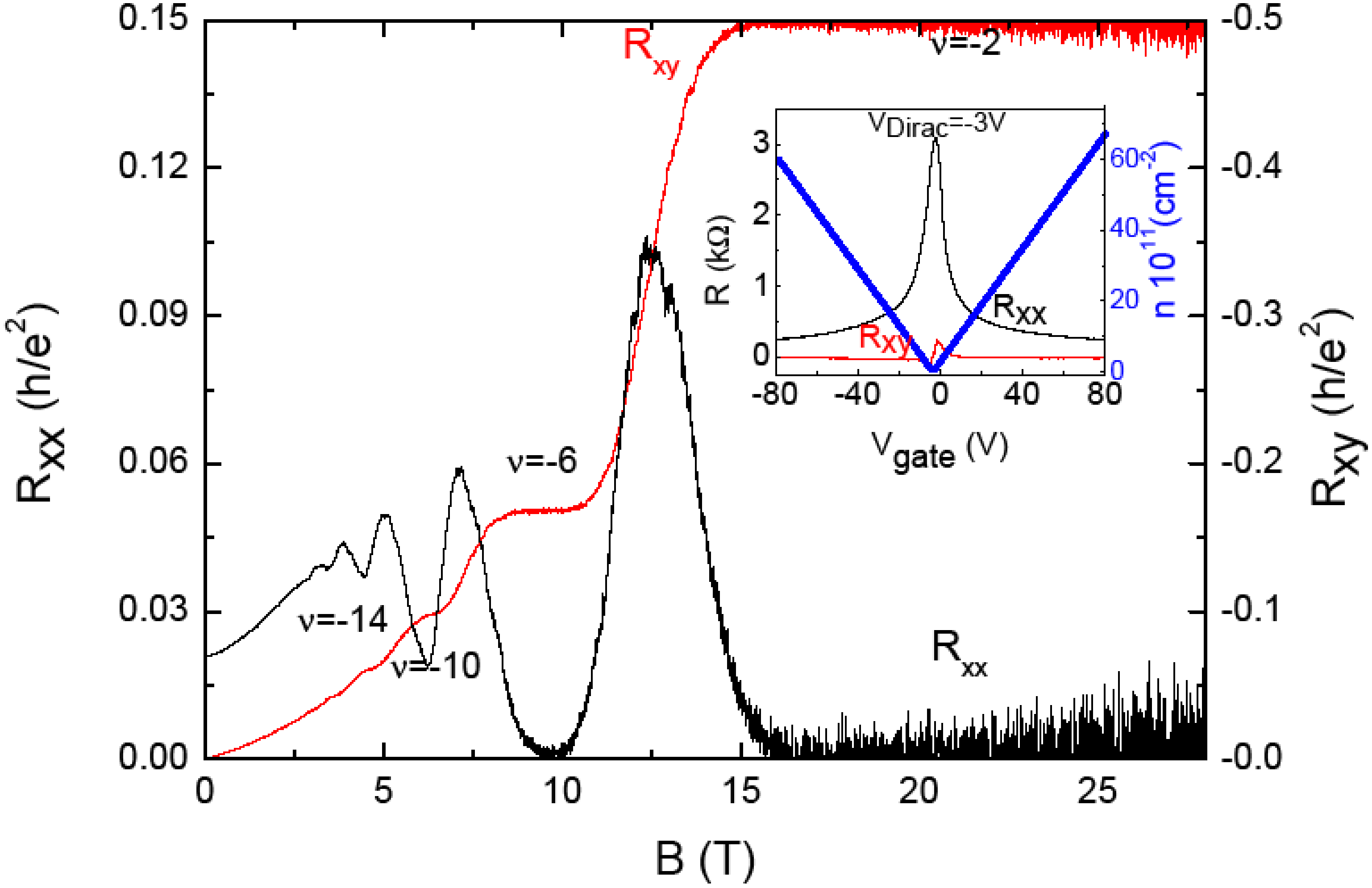


R_{xx} diverges with T at the Dirac point

Quantization of the R_{xy}→QHE

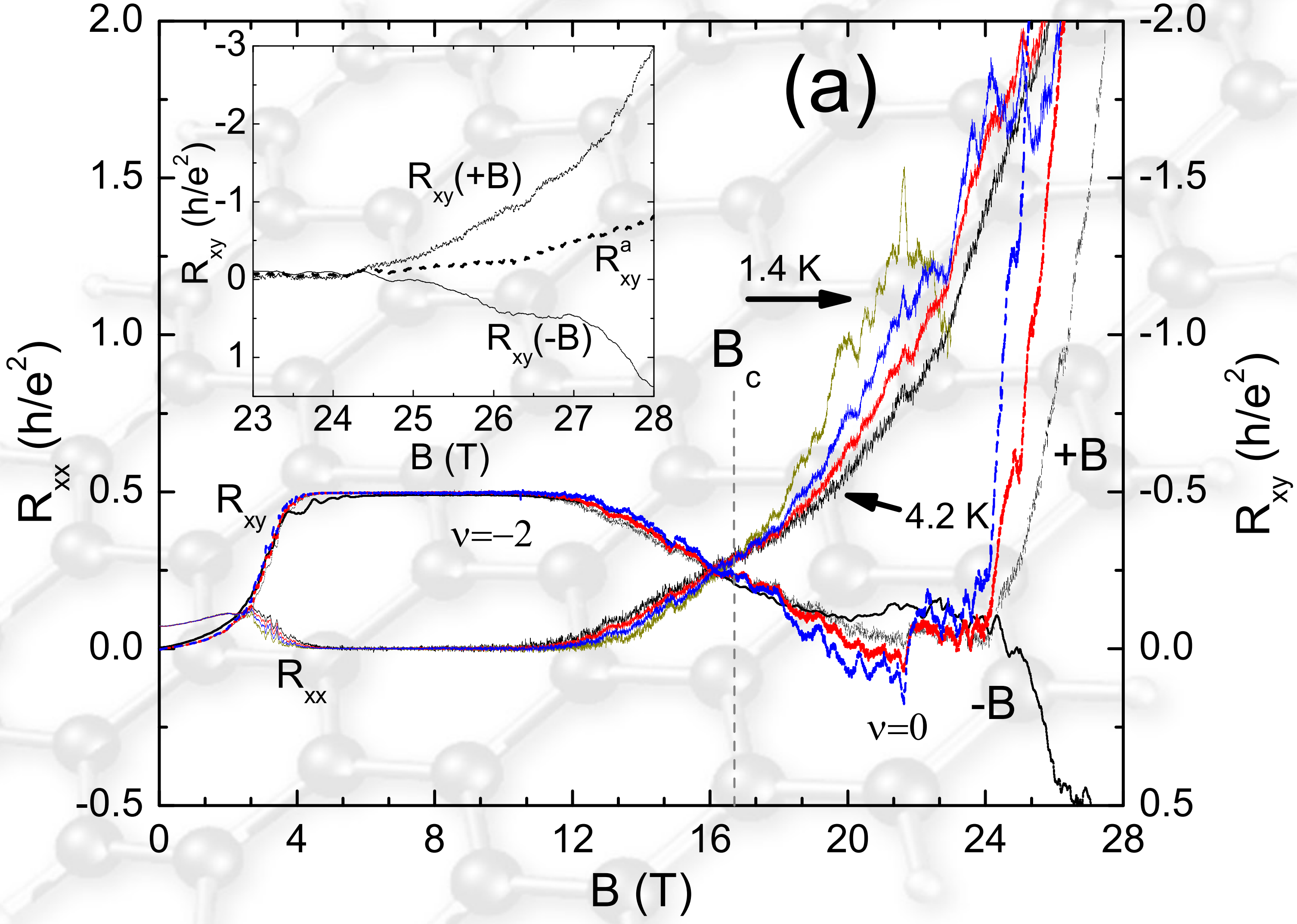


QHE by varying the magnetic field.



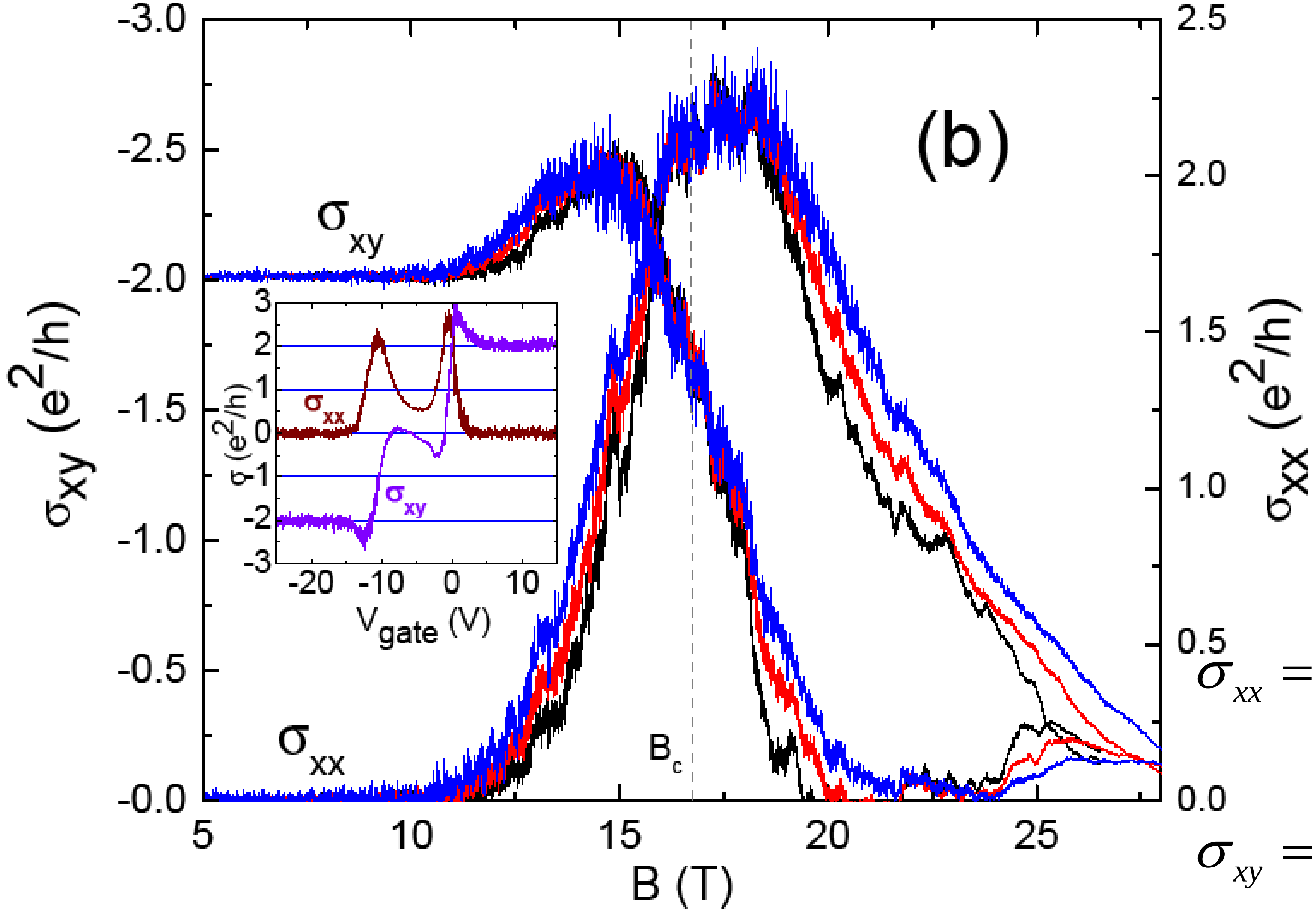
T =4.2 K
V_{gate} = -20 V

Crossing point.T independence.



V_{gate}=-8V

Conductivity.



$$\sigma_{xx} = \frac{R_{xx}}{R_{xx}^2 + R_{xy}^2}$$

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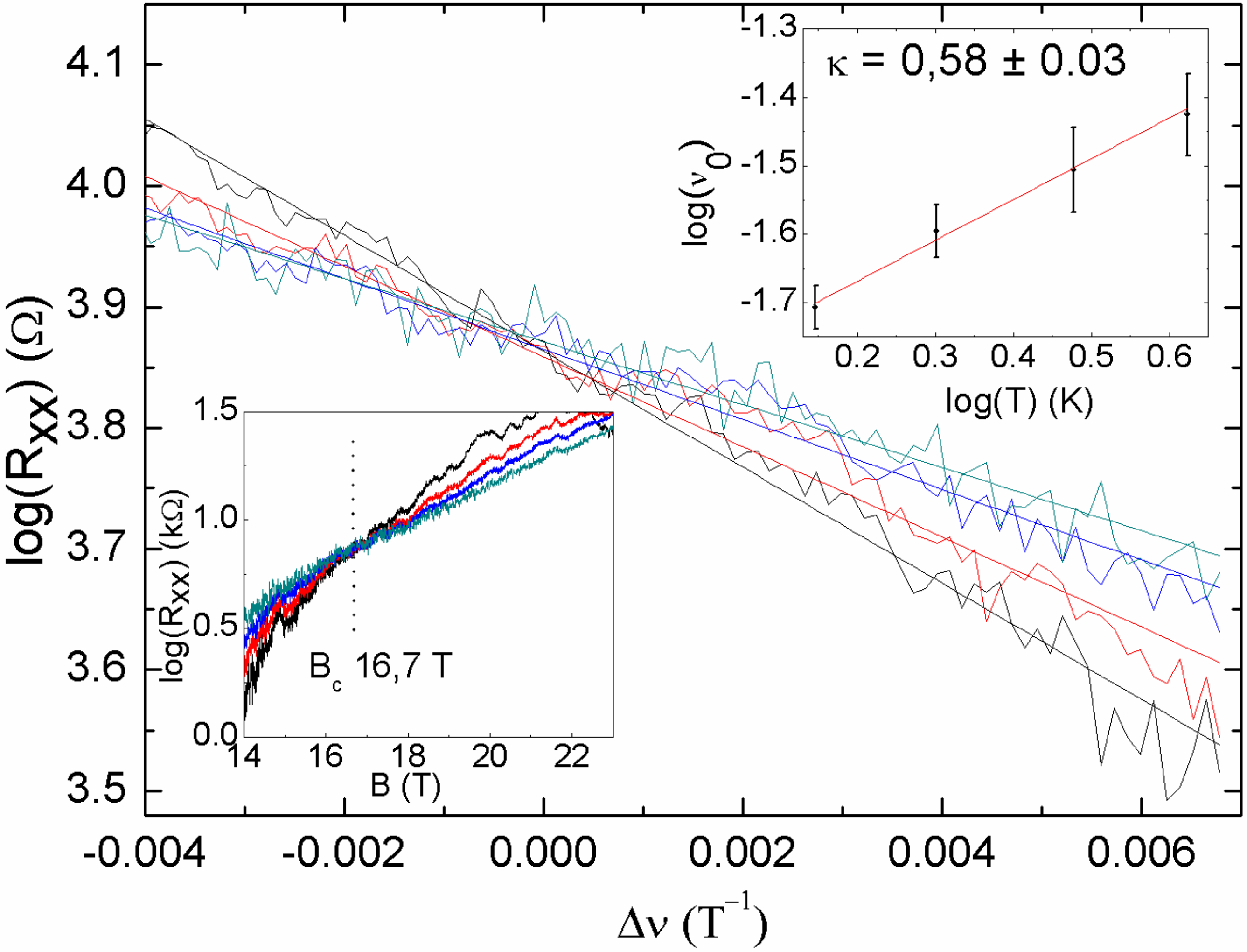
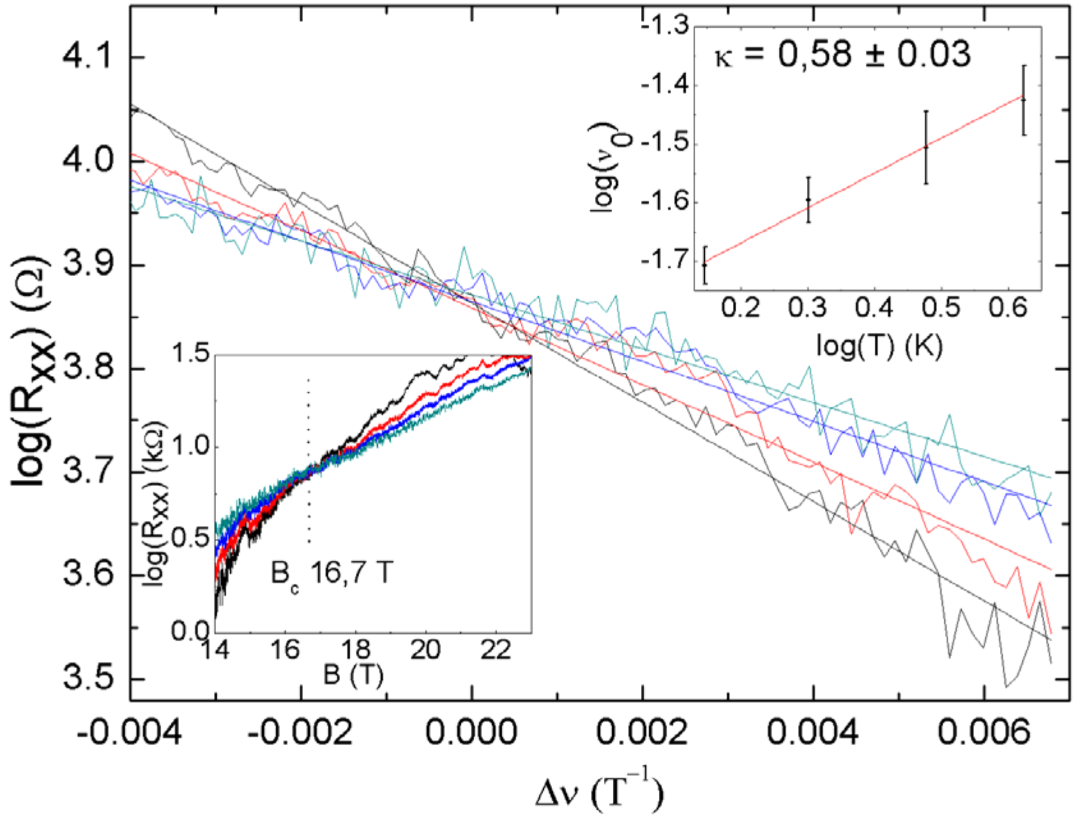
Plateau-Insulator transition



Plateau-Insulator transition



V_{gate}=-8V

$$\Delta\nu = \frac{1}{B} - \frac{1}{B_C}$$

$$B_C = 16.7T$$

$$\rho_{xx}(T) = e^{-\Delta\nu / \nu_0(T)}$$

$$\nu_0 \propto T^{-k}$$

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Conclusions and future work

- Sample fabrication.
- Automatic Raman characterisation.
- Systematic study of the temperature dependence of the resistivity.
- Evidence of a crossing point in $R_{xy.}$
- Plateau to insulator transition.
- Critical exponent K=0.58. First observation in a true 2D system. Universality of K.
- Measure the Hall effect going down with T into the milikelvin regime

Thank you for your attention