Electron Transport in Graphitic Systems

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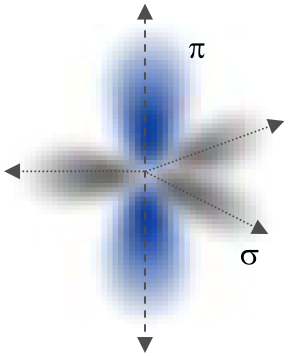
IN THE CITY OF NEW YORK

Columbia University and the National Science Foundation
Center for
Electron
Transport
in Molecular Nanostructures

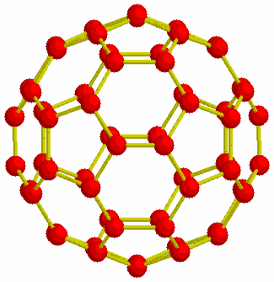
SP$_2$ Carbon: 0-Dimension to 3-Dimension



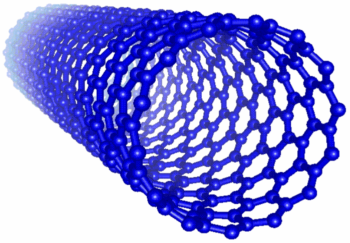
Atomic orbital sp$_2$

0D **1D** **2D** **3D**

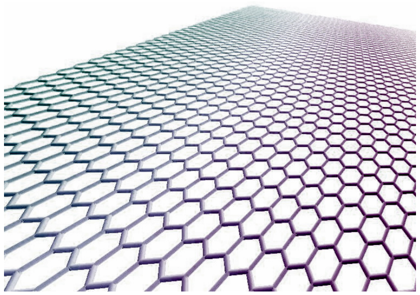
Fullerenes (C$_{60}$)



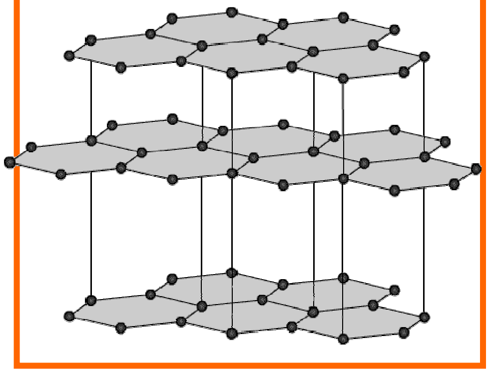
Carbon Nanotubes



Graphene

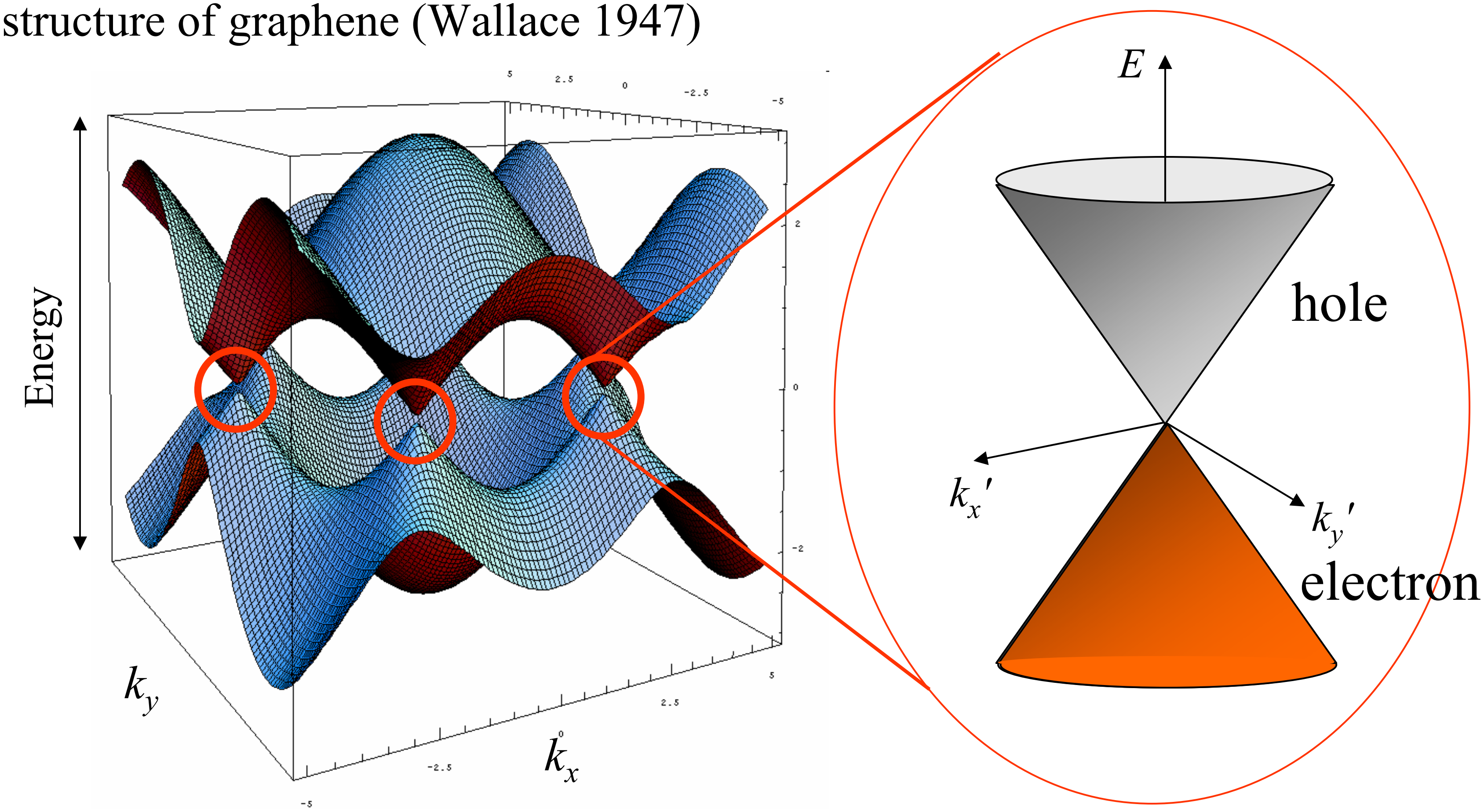


Graphite



Graphene : Dirac Particles in 2-dimension

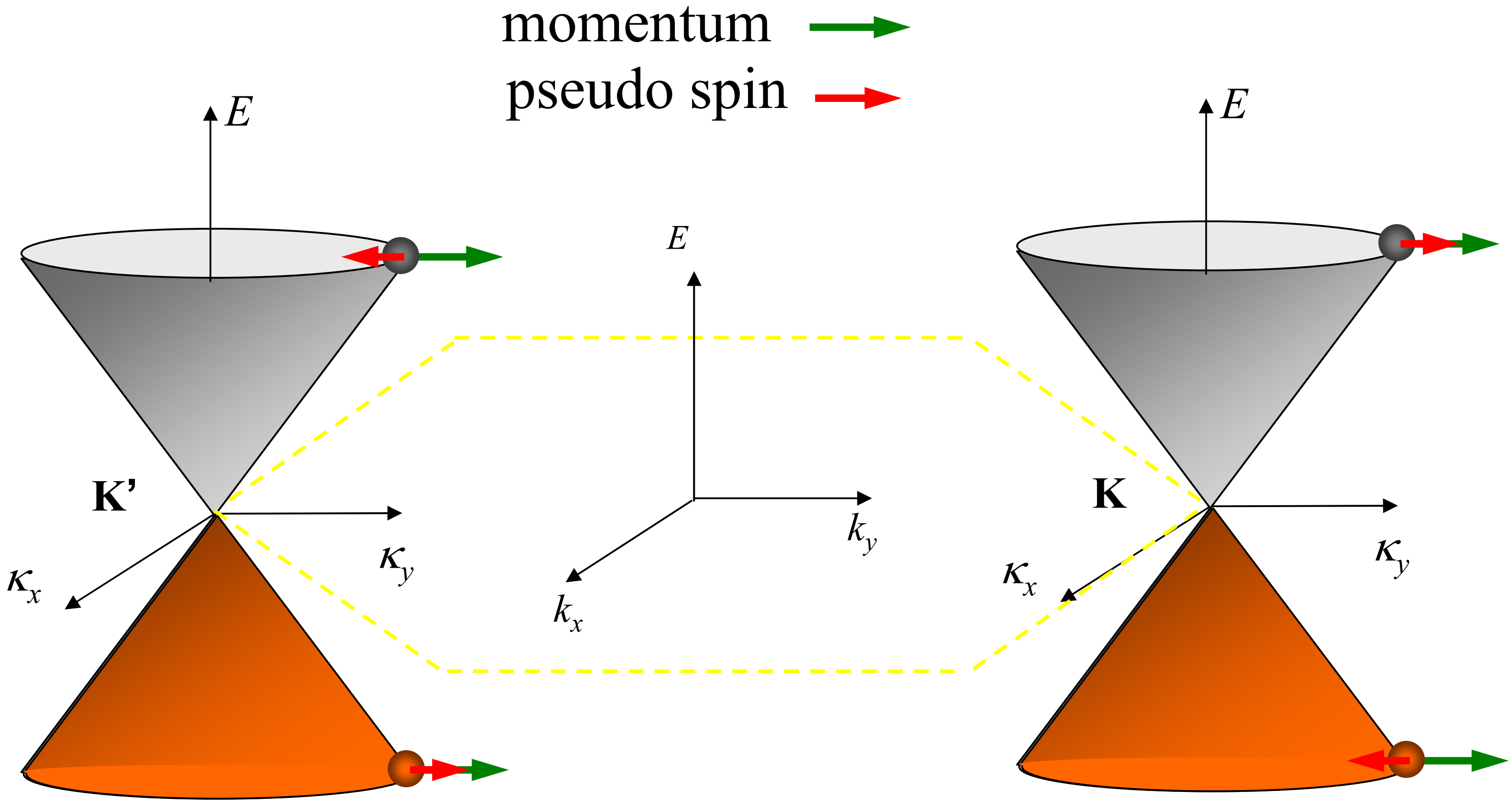
Band structure of graphene (Wallace 1947)



$$E \approx \hbar v_F \left| \vec{k}'_\perp \right|$$

Zero effective mass particles moving with a constant speed v_F

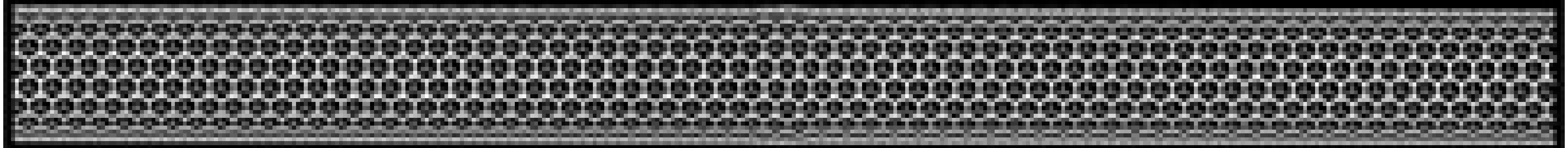
Dirac Fermions in Graphene : “Helicity”



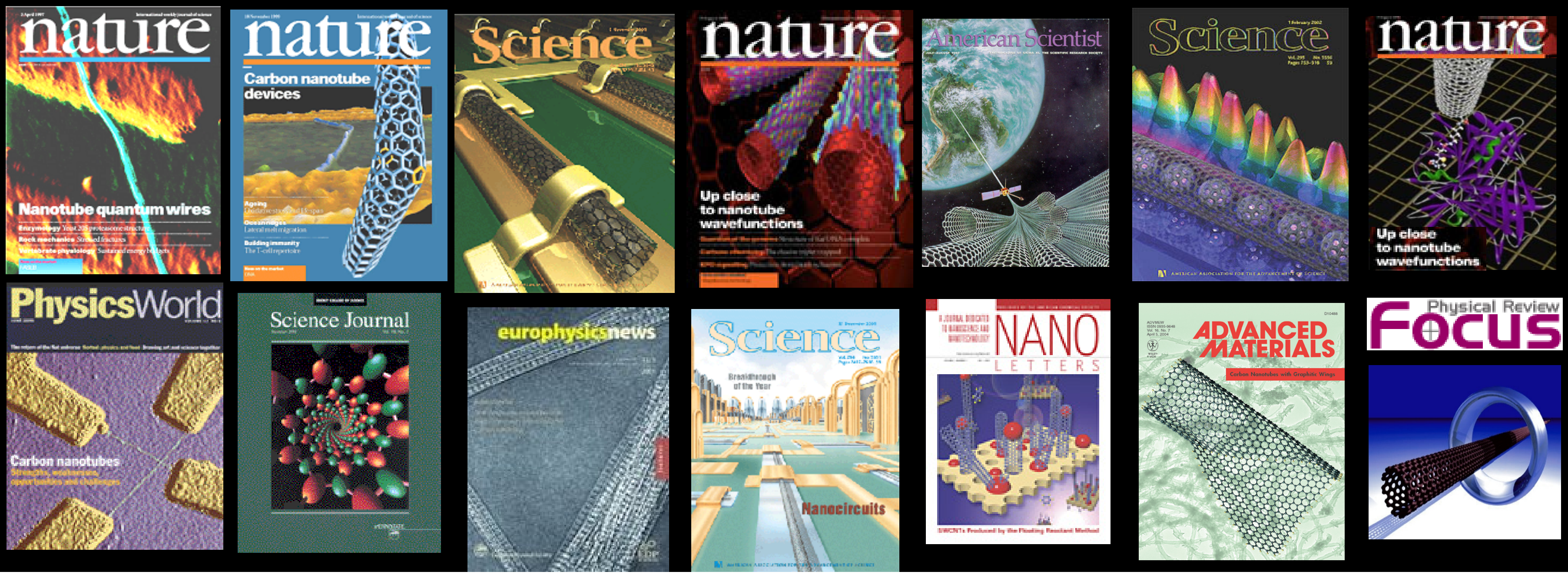
$$H_{eff} = \hbar v_F \vec{\sigma}^{*} \cdot \vec{k}_{\perp}$$

$$H_{eff} = \hbar v_F \vec{\sigma} \cdot \vec{k}_{\perp}$$

Single Wall Carbon Nanotube

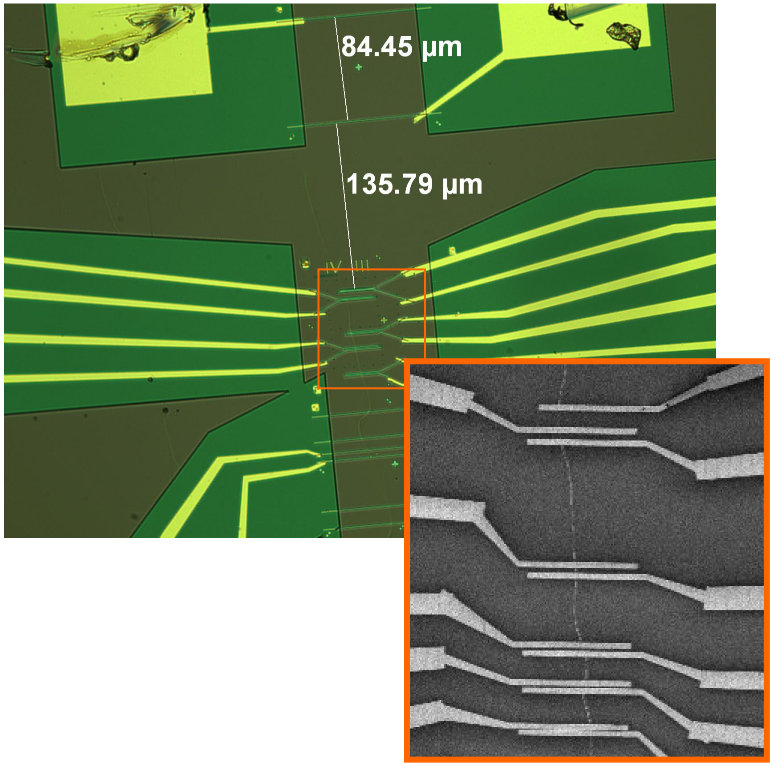


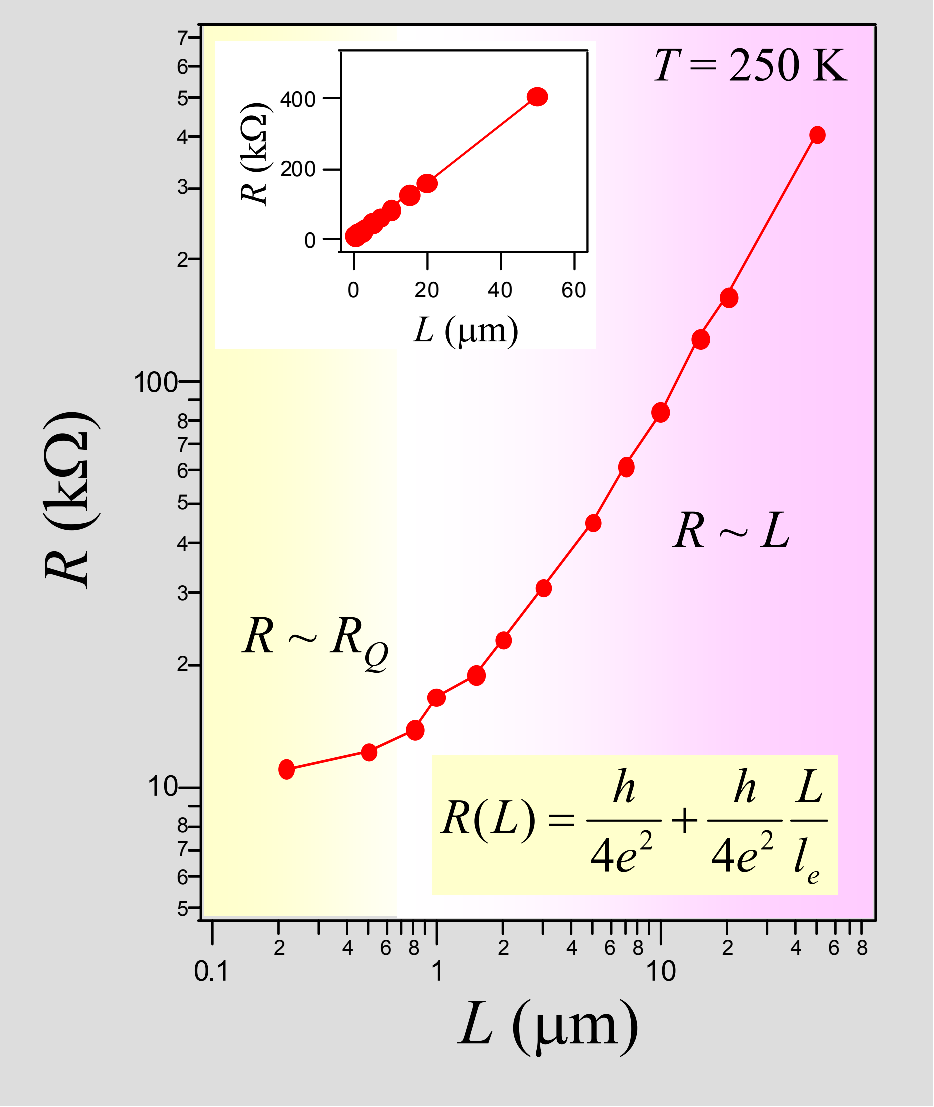
…. since 1991



Electron Transport in Long Single Walled Nanotubes

Multi-terminal Device with Pd contact



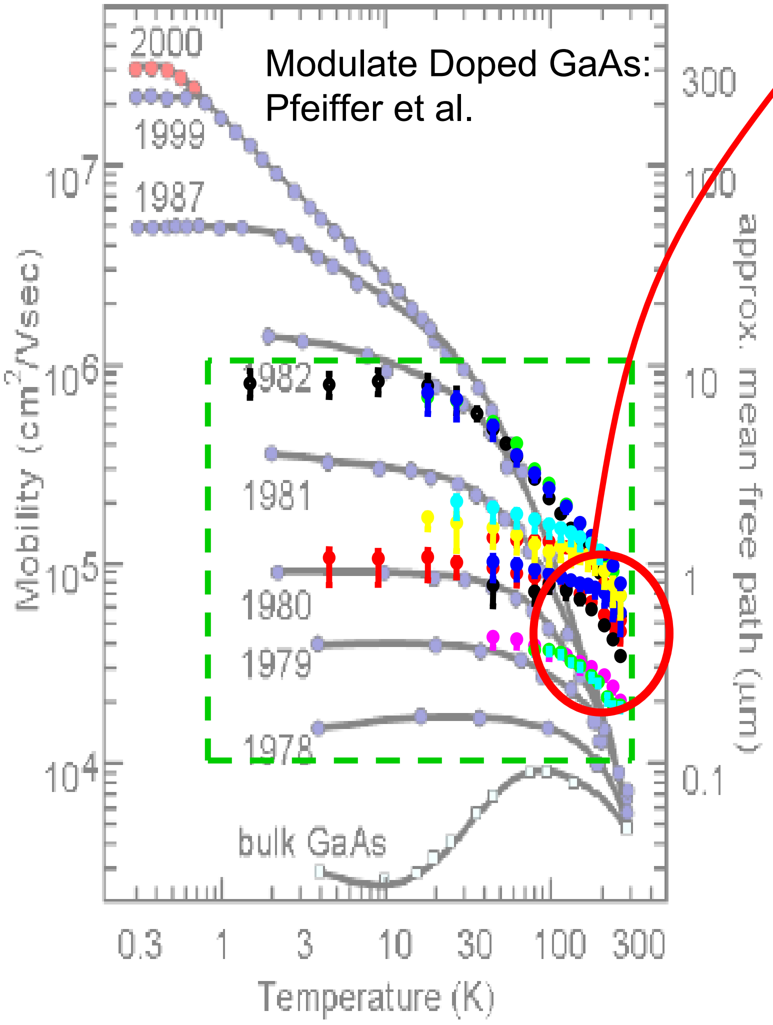


$$R(L) = \frac{h}{4e^2} + \frac{h}{4e^2}\frac{L}{l_e}$$

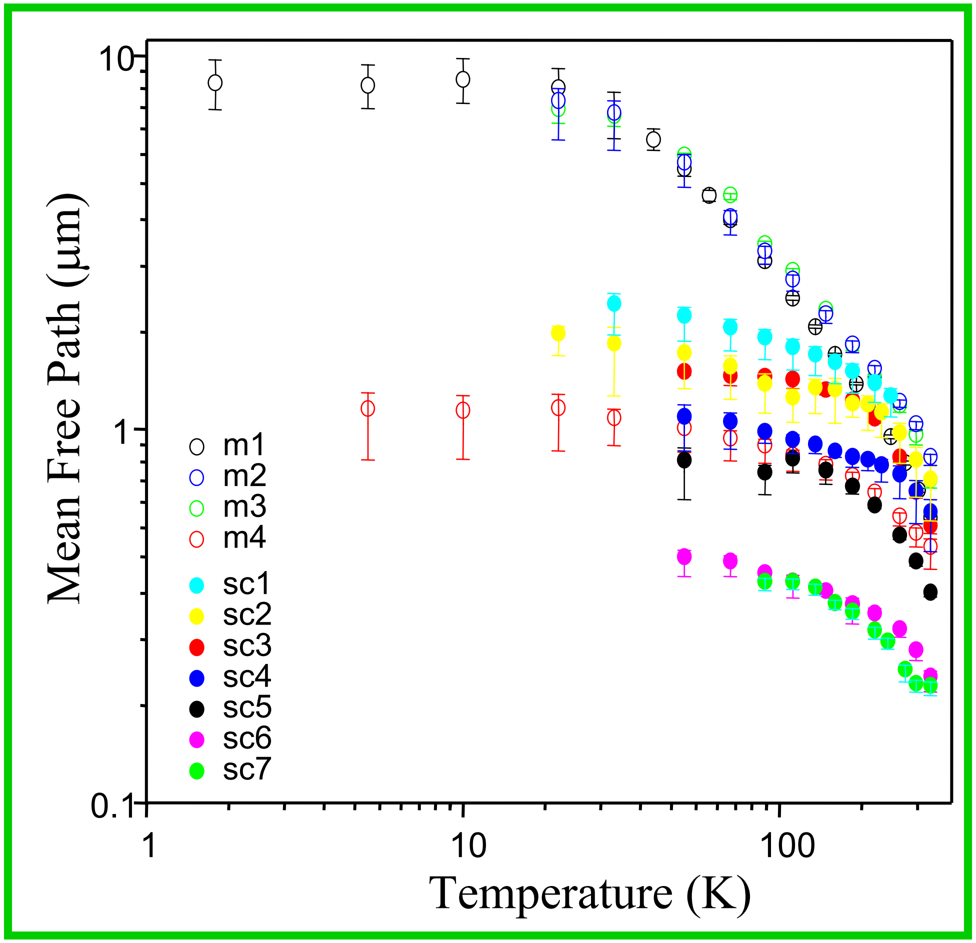
* Scaling behavior of resistance: $R(L)$

Purewall, Hong, Ravi, Chandra, Hone, and P. Kim PRL (2007)

Electron Mean Free Path of Nanotubes



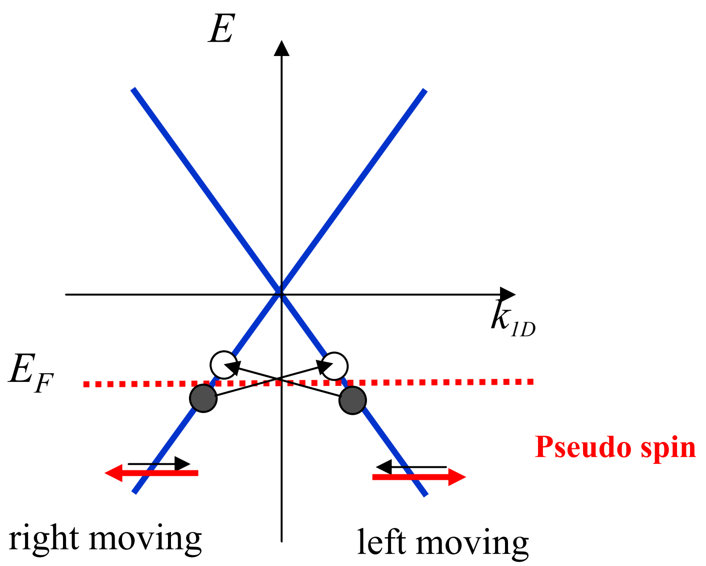
Room temperature mean free path > 0.2 μm



M. Purewall, B. Hong, A. Ravi, B. Chnadra, J. Hone and P. Kim, PRL (2007)

Extremely Long Mean Free Path: Hidden Symmetry ?

1D band structure of nanotubes



- Small momentum transfer backward scattering becomes inefficient since it requires pseudo spin flipping.

Journal of the Physical Society of Japan
Vol. 67, No. 8, August, 1998, pp. 2857–2862

Berry's Phase and Absence of Back Scattering in Carbon Nanotubes

Tsuneya ANDO, Takeshi NAKANISHI,[1] and Riichiro SAITO[2]

Institute for Solid State Physics, University of Tokyo
7–22–1 Minato-ku, Roppongi, Tokyo 106

[1] *The Institute of Physical and Chemical Research (RIKEN)*
2–1 Hirosawa, Wako-shi, Saitama 351-01

[2] *Department of Electronics Engineering*
University of Electro-Communications, Chofugaoka, Chofu, Tokyo 182

(Received March 16, 1998)

The absence of back scattering in carbon nanotubes is shown to be ascribed to Berry's phase which corresponds to a sign change of the wave function under a spin rotation of a neutrino-like particle in a two-dimensional graphite. Effects of trigonal warping of the bands appearing in a higher order $\boldsymbol{k}\cdot\boldsymbol{p}$ approximation are shown to give rise to a small probability of back scattering.

VOLUME 83, NUMBER 24 PHYSICAL REVIEW LETTERS 13 DECEMBER 1999

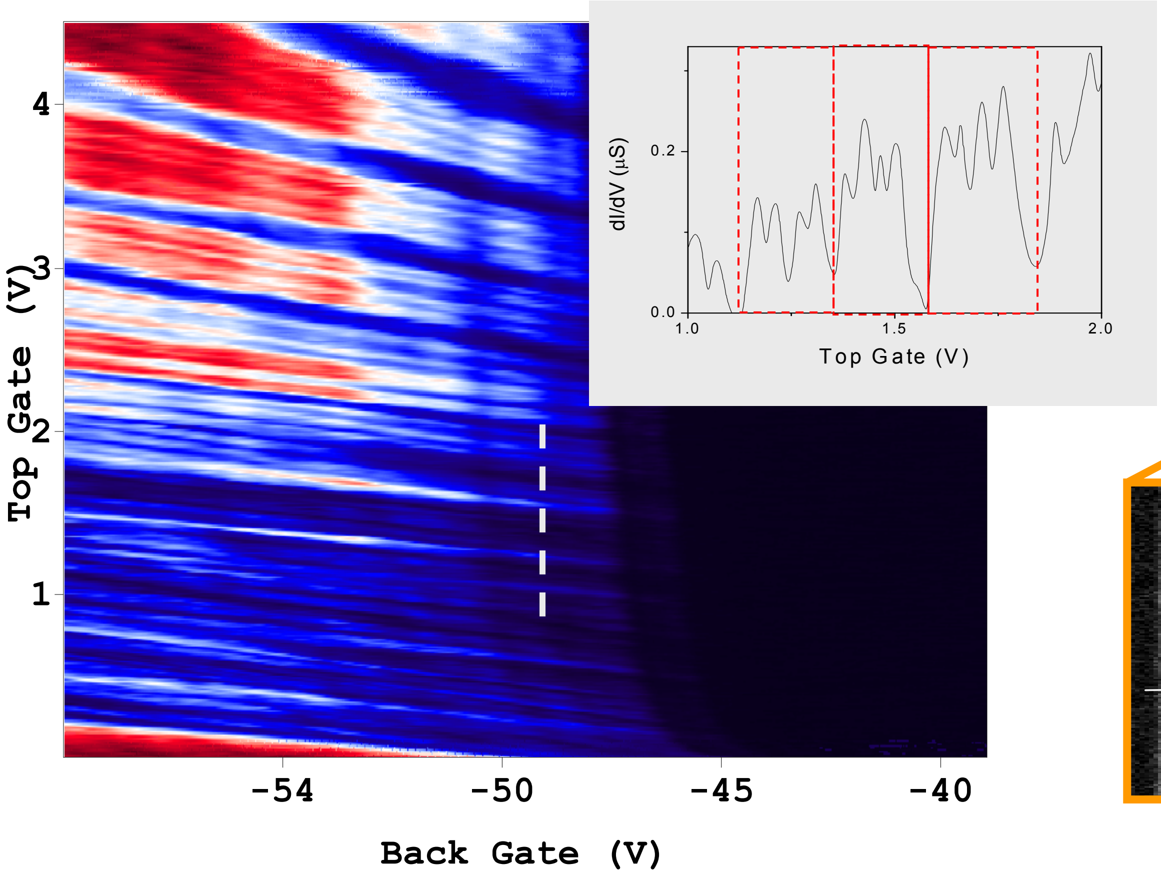
Disorder, Pseudospins, and Backscattering in Carbon Nanotubes

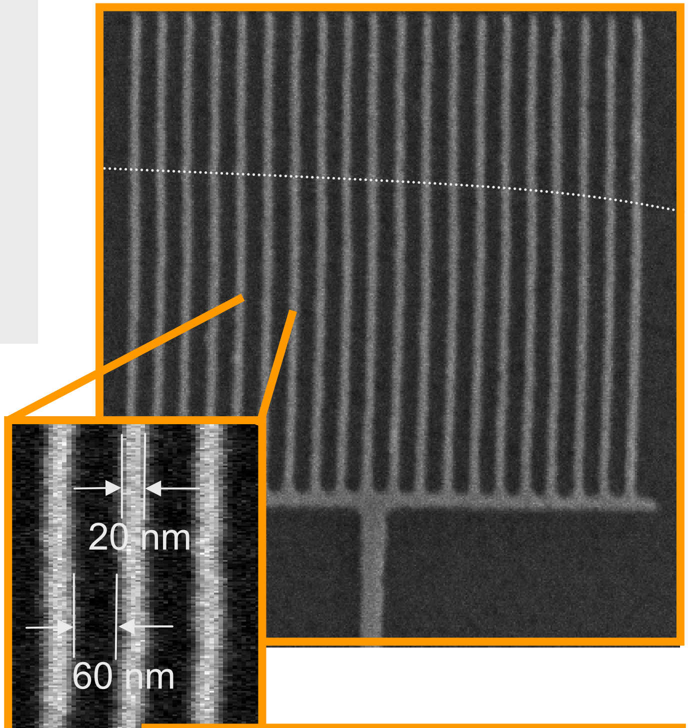
Paul L. McEuen, Marc Bockrath, David H. Cobden,* Young-Gui Yoon, and Steven G. Louie
Department of Physics, University of California, and Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 7 June 1999)

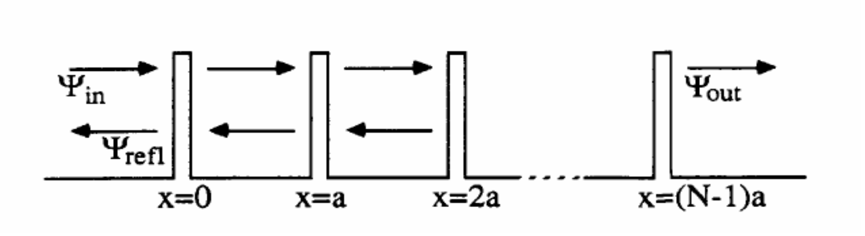
We address the effects of disorder on the conducting properties of metal and semiconducting carbon nanotubes. Experimentally, the mean free path is found to be much larger in metallic tubes than in doped semiconducting tubes. We show that this result can be understood theoretically if the disorder potential is long ranged. The effects of a pseudospin index that describes the internal sublattice structure of the states lead to a suppression of scattering in metallic tubes, but not in semiconducting tubes. This conclusion is supported by tight-binding calculations.

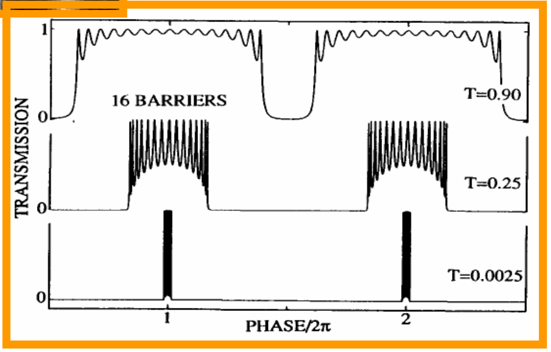
Carbon Nanotube Superlattice

Purewal, Zuev, Jarillo-Herrero, Kim (2007)



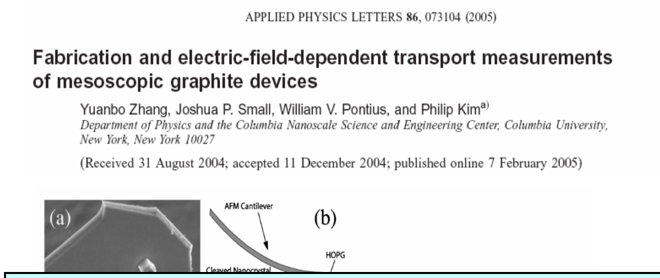






Discovery of Grphene

by ~ 2004

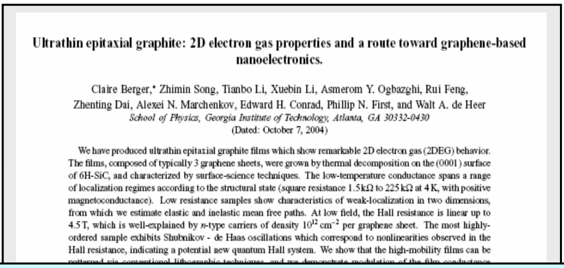


APPLIED PHYSICS LETTERS **86**, 073104 (2005)

Fabrication and electric-field-dependent transport measurements of mesoscopic graphite devices

Yuanbo Zhang, Joshua P. Small, William V. Pontius, and Philip Kim[a)]
Department of Physics and the Columbia Nanoscale Science and Engineering Center, Columbia University, New York, New York 10027

(Received 31 August 2004; accepted 11 December 2004; published online 7 February 2005)



Ultrathin epitaxial graphite: 2D electron gas properties and a route toward graphene-based nanoelectronics.

Claire Berger,* Zhimin Song, Tianbo Li, Xuebin Li, Asmerom Y. Ogbazghi, Rui Feng,
Zhenting Dai, Alexei N. Marchenkov, Edward H. Conrad, Phillip N. First, and Walt A. de Heer
School of Physics, Georgia Institute of Technology, Atlanta, GA 30332-0430

(Dated: October 7, 2004)

We have produced ultrathin epitaxial graphite films which show remarkable 2D electron gas (2DEG) behavior. The films, composed of typically 3 graphene sheets, were grown by thermal decomposition on the (0001) surface of 6H-SiC, and characterized by surface-science techniques. The low-temperature conductance spans a range of localization regimes according to the structural state (square resistance 1.5 kΩ to 225 kΩ at 4 K, with positive magnetoconductance). Low resistance samples show characteristics of weak-localization in two dimensions, from which we estimate elastic and inelastic mean free paths. At low field, the Hall resistance is linear up to 4.5 T, which is well-explained by *n*-type carriers of density 10^{12} cm^{-2} per graphene sheet. The most highly-ordered sample exhibits Shubnikov - de Haas oscillations which correspond to nonlinearities observed in the Hall resistance, indicating a potential new quantum Hall system. We show that the high-mobility films can be

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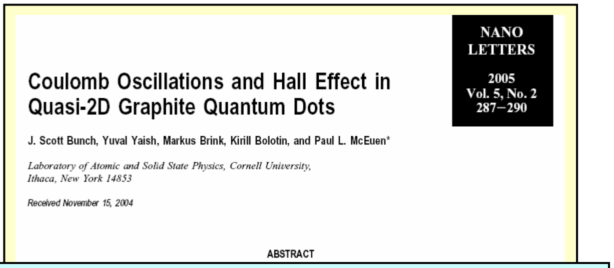


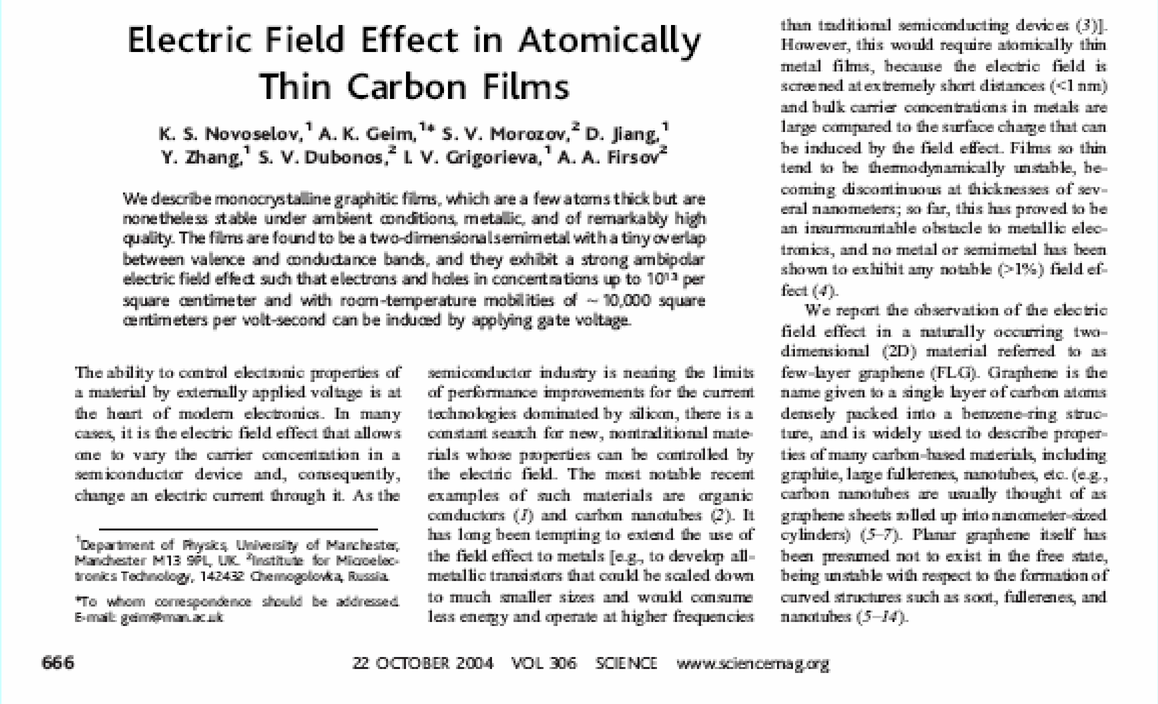
NANO LETTERS
2005
Vol. 5, No. 2
287−290

Coulomb Oscillations and Hall Effect in Quasi-2D Graphite Quantum Dots

J. Scott Bunch, Yuval Yaish, Markus Brink, Kirill Bolotin, and Paul L. McEuen*
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853

Received November 15, 2004

ABSTRACT



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.

The ability to control electronic properties of a material by externally applied voltage is at the heart of modern electronics. In many cases, it is the electric field effect that allows one to vary the carrier concentration in a semiconductor device and, consequently, change an electric current through it. As the semiconductor industry is nearing the limits of performance improvements for the current technologies dominated by silicon, there is a constant search for new, nontraditional materials whose properties can be controlled by the electric field. The most notable recent examples of such materials are organic conductors (*1*) and carbon nanotubes (*2*). It has long been tempting to extend the use of the field effect to metals [e.g., to develop all-metallic transistors that could be scaled down to much smaller sizes and would consume less energy and operate at higher frequencies than traditional semiconducting devices (*3*)]. However, this would require atomically thin metal films, because the electric field is screened at extremely short distances (<1 nm) and bulk carrier concentrations in metals are large compared to the surface charge that can be induced by the field effect. Films so thin tend to be thermodynamically unstable, becoming discontinuous at thicknesses of several nanometers; so far, this has proved to be an insurmountable obstacle to metallic electronics, and no metal or semimetal has been shown to exhibit any notable (>1%) field effect (*4*).

We report the observation of the electric field effect in a naturally occurring two-dimensional (2D) material referred to as few-layer graphene (FLG). Graphene is the name given to a single layer of carbon atoms densely packed into a benzene-ring structure, and is widely used to describe properties of many carbon-based materials, including graphite, large fullerenes, nanotubes, etc. (e.g., carbon nanotubes are usually thought of as graphene sheets rolled up into nanometer-sized cylinders) (*5*–*7*). Planar graphene itself has been presumed not to exist in the free state, being unstable with respect to the formation of curved structures such as soot, fullerenes, and nanotubes (*5*–*14*).

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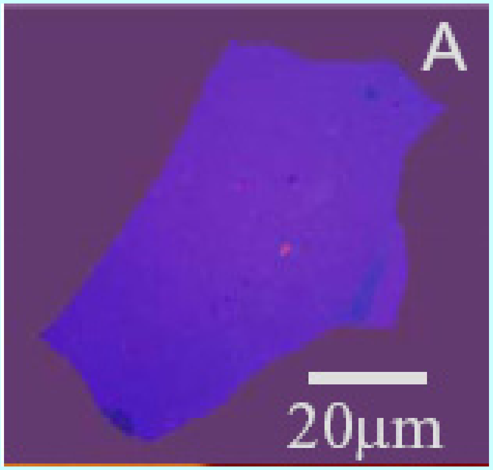
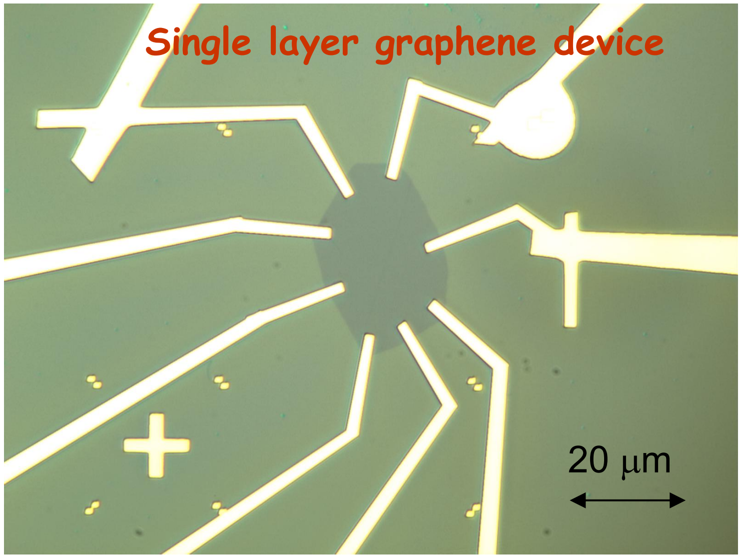
[1]Department of Physics, University of Manchester, Manchester M13 9PL, UK. [2]Institute for Microelectronics Technology, 142432 Chernogolovka, Russia.

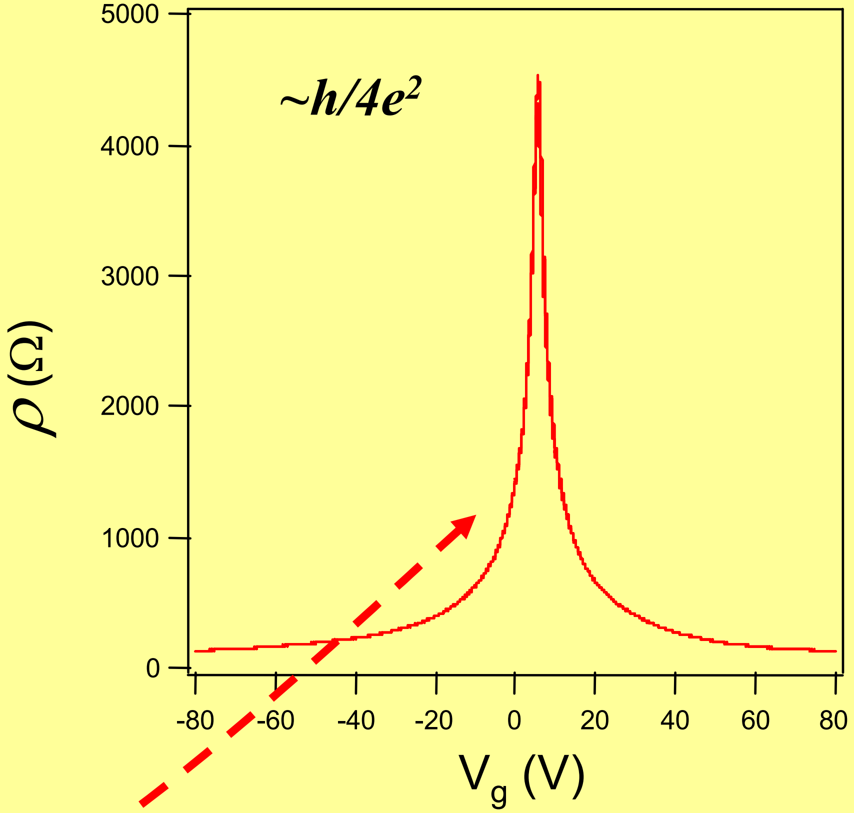
*To whom correspondence should be addressed. E-mail: geim@man.ac.uk

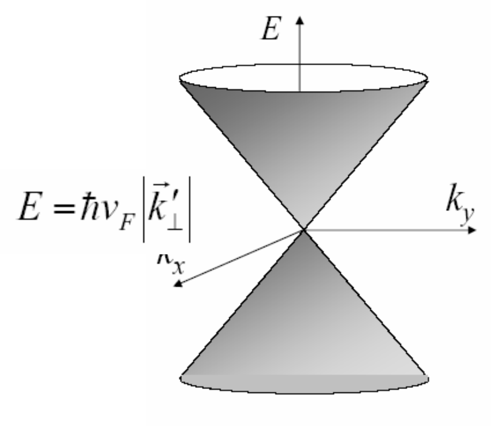


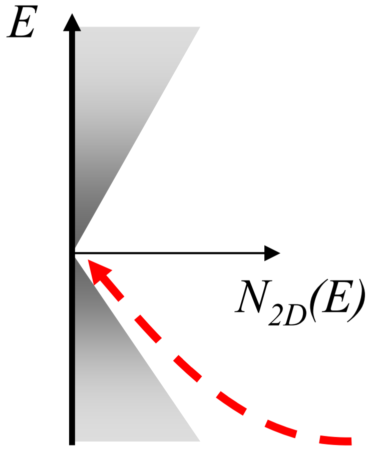
Transport Single Layer Graphene



Resistivity vs Gate Voltage







$$\rho^{-1} = e^2 v_F \, l_e \, N_{2D}$$

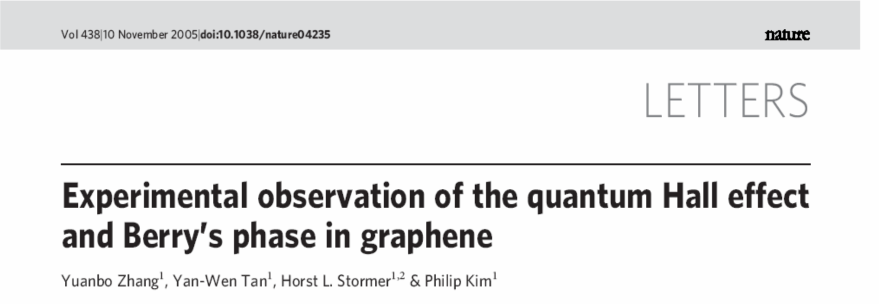
Quantum Hall Effect in Graphene

Vol 438|10 November 2005|**doi:10.1038/nature04233** **nature**

LETTERS

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]

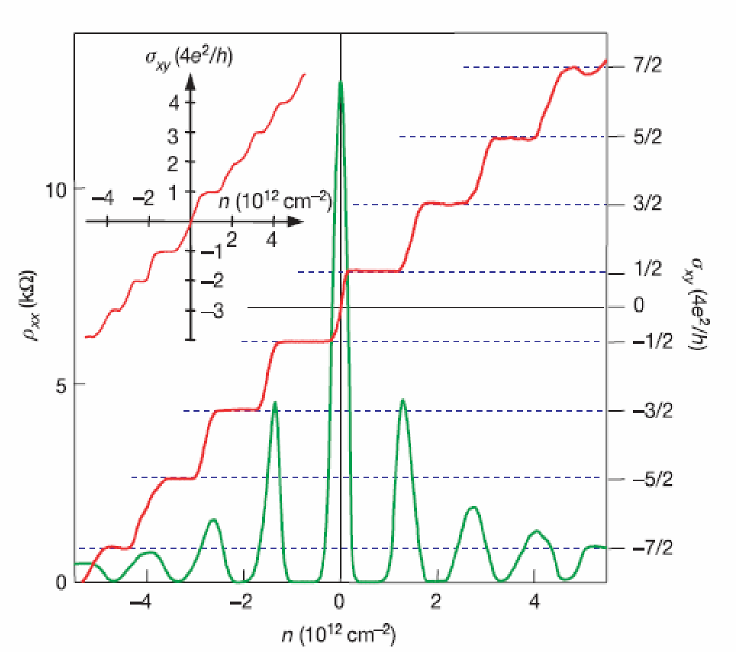


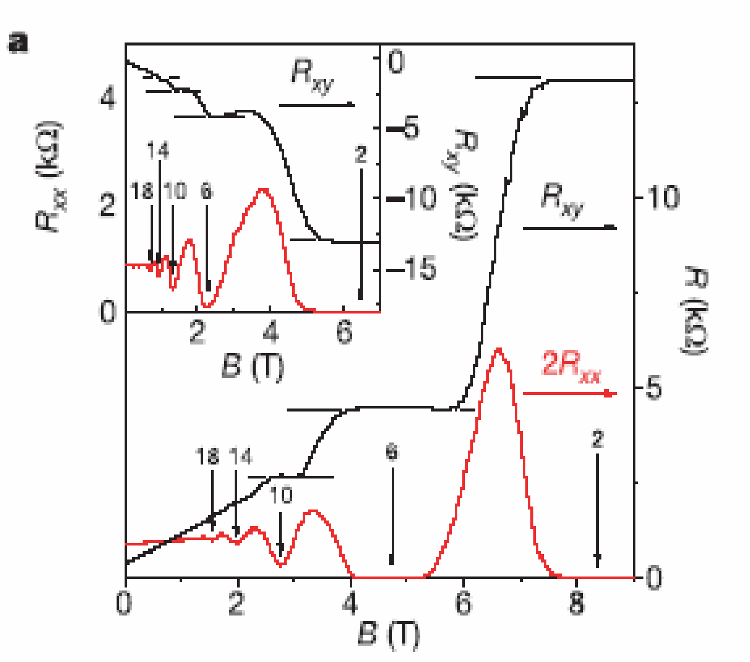
Vol 438|10 November 2005|**doi:10.1038/nature04235** **nature**

LETTERS

Experimental observation of the quantum Hall effect and Berry's phase in graphene

Yuanbo Zhang[1], Yan-Wen Tan[1], Horst L. Stormer[1,2] & Philip Kim[1]





Quantization:

$$R_{xy}^{-1} = 4\left(n+\frac{1}{2}\right)\frac{e^2}{h}$$

Relativistic Landau Level and Half Integer QHE

Haldane, PRL (1988)

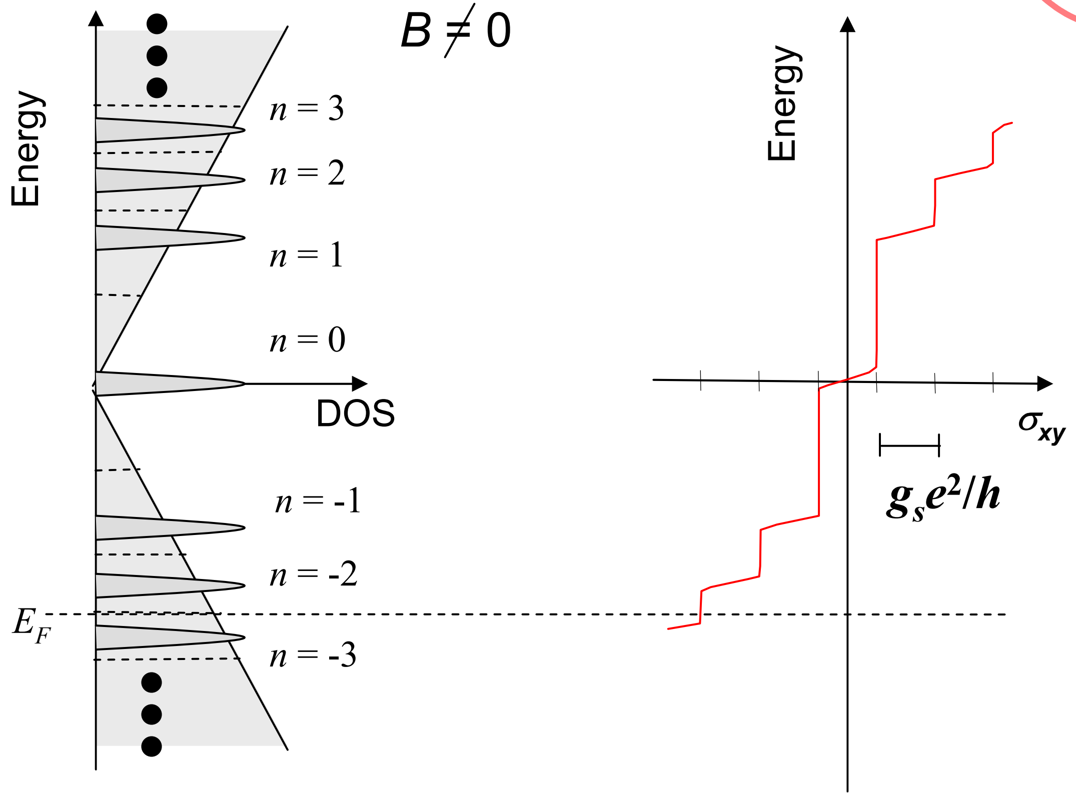
Landau Level $E_n = \pm\sqrt{2e\hbar v_F^2 |n| B}$

Landau Level Degeneracy

$g_s = 4$

2 for spin and 2 for sublattice

$E_1 \sim 300$ K $[B(T)]^{1/2}$



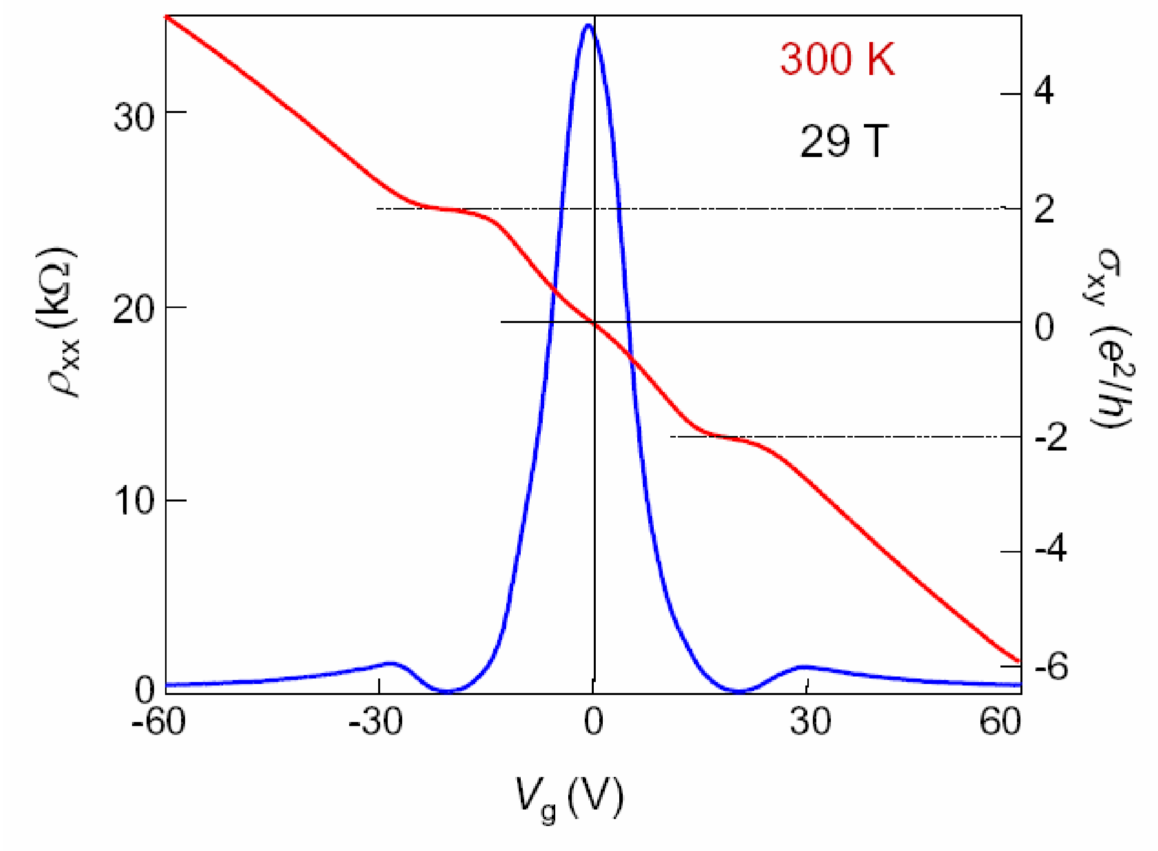
Quantized Condition

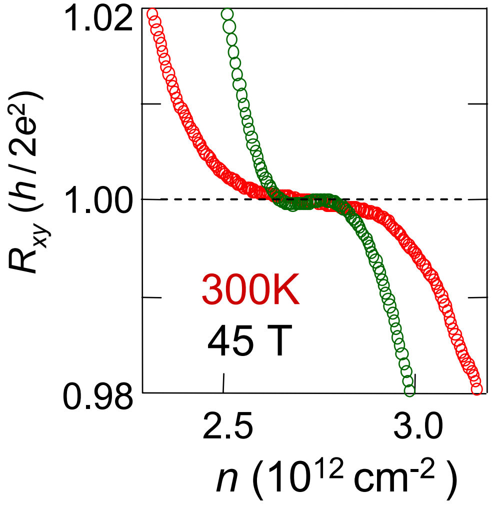
$$R_{xy}^{-1} = \pm g_s (n + \frac{1}{2}) \frac{e^2}{h}$$

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

T. Ando et al (2002)

Room Temperature Quantum Hall Effect





Deviation < 0.3%

$$E_n = \pm\sqrt{2e\hbar v_F^2 |n| B}$$

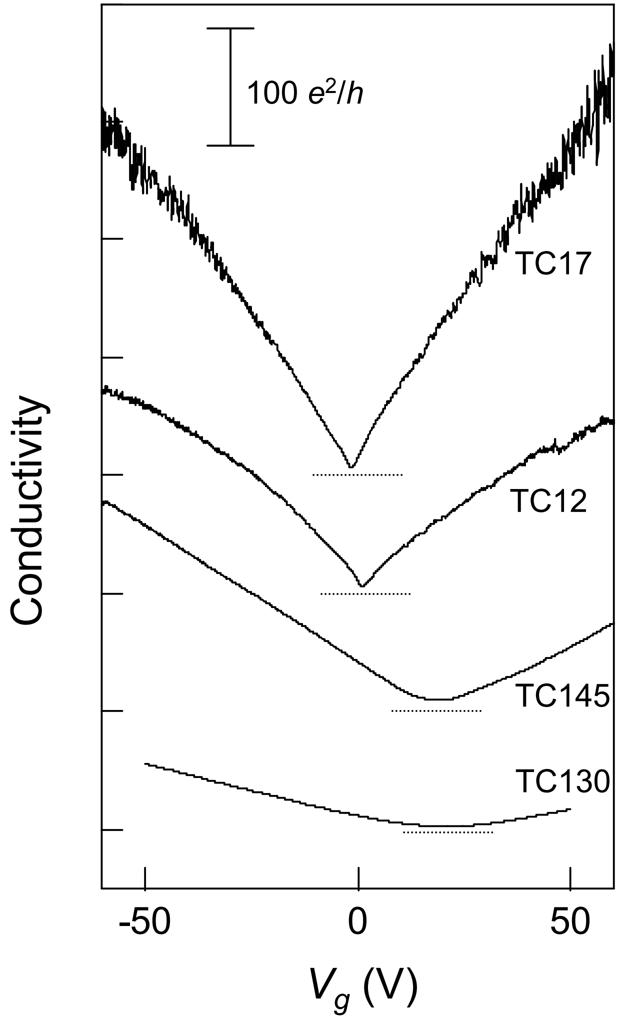
$$E_1 \sim 100 \text{ meV @ } 5 \text{ T}$$

Novoselov, Jiang, Zhang, Morozov, Stormer, Zeitler, Maan, Boebinger, Kim, and Geim *Science* (2007)

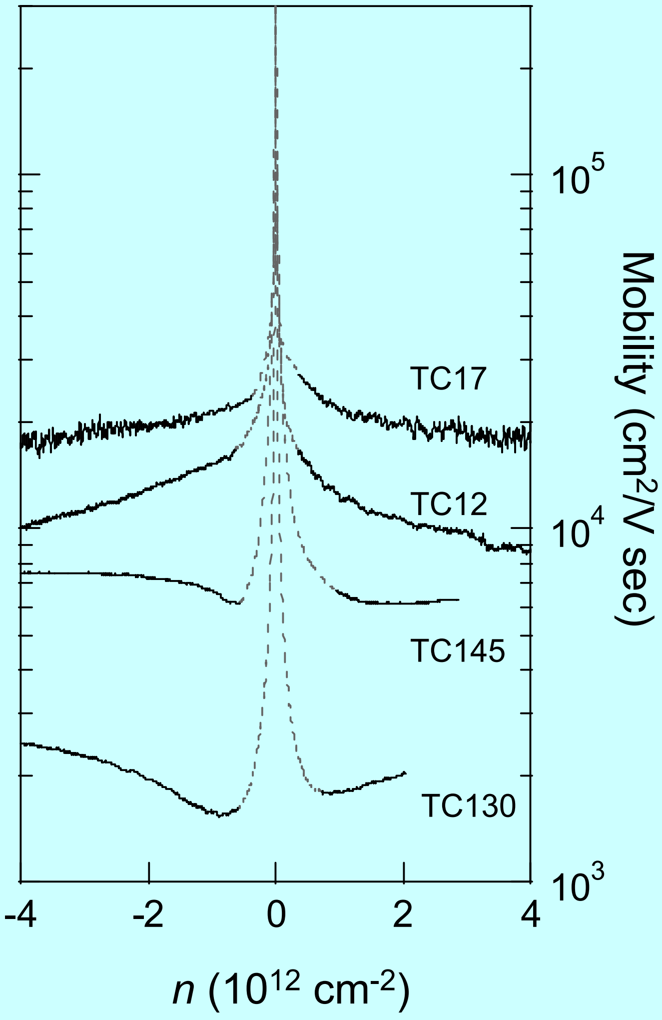
Conductivity, Mobility, & Mean Free Path

Tan at al, PRL (2007)

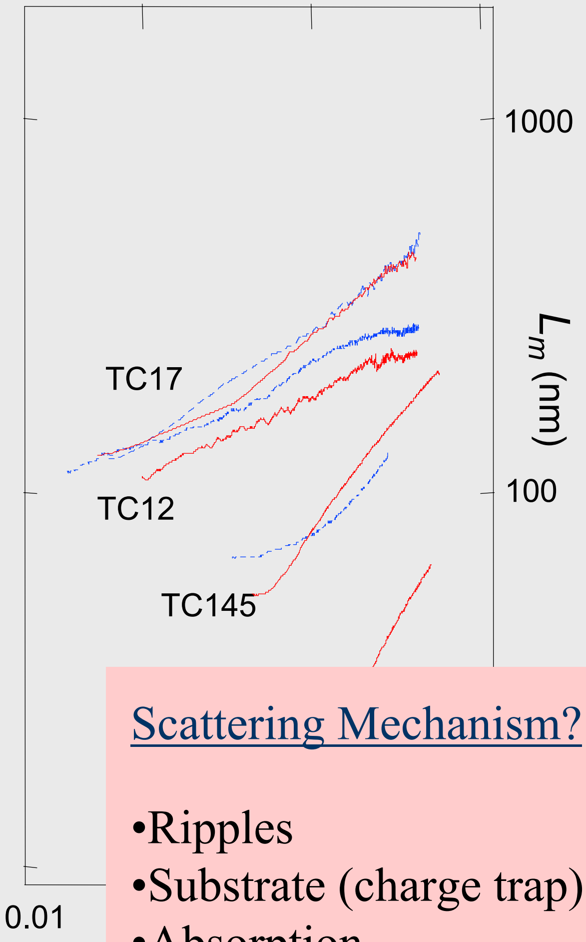
$$\sigma = en\mu = \frac{e^2}{\hbar}\ell\sqrt{\frac{n}{\pi}}$$



Mobility



Mean free path

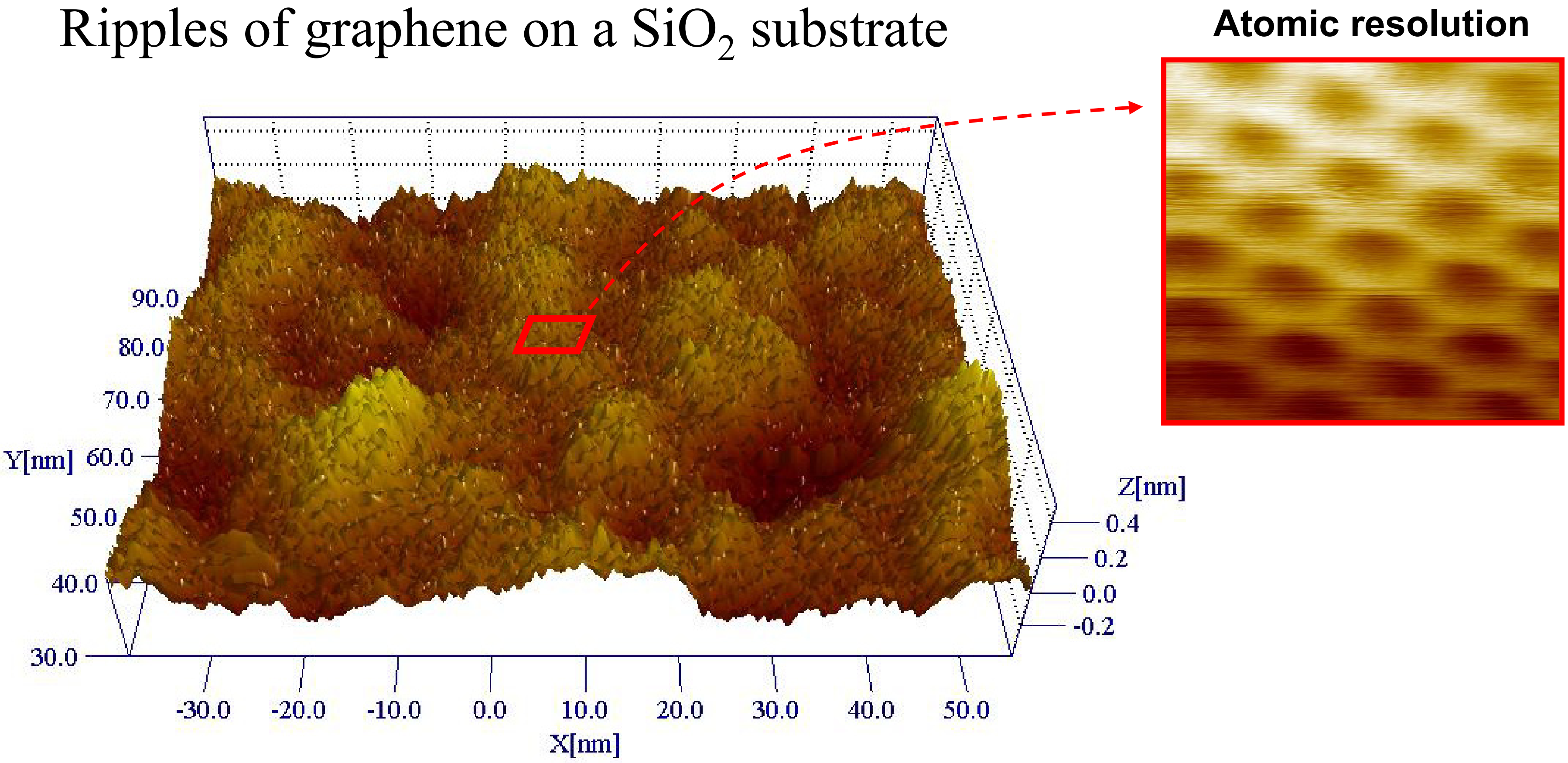


Scattering Mechanism?

- Ripples
- Substrate (charge trap)
- Absorption
- Structural defects

STM on Graphene

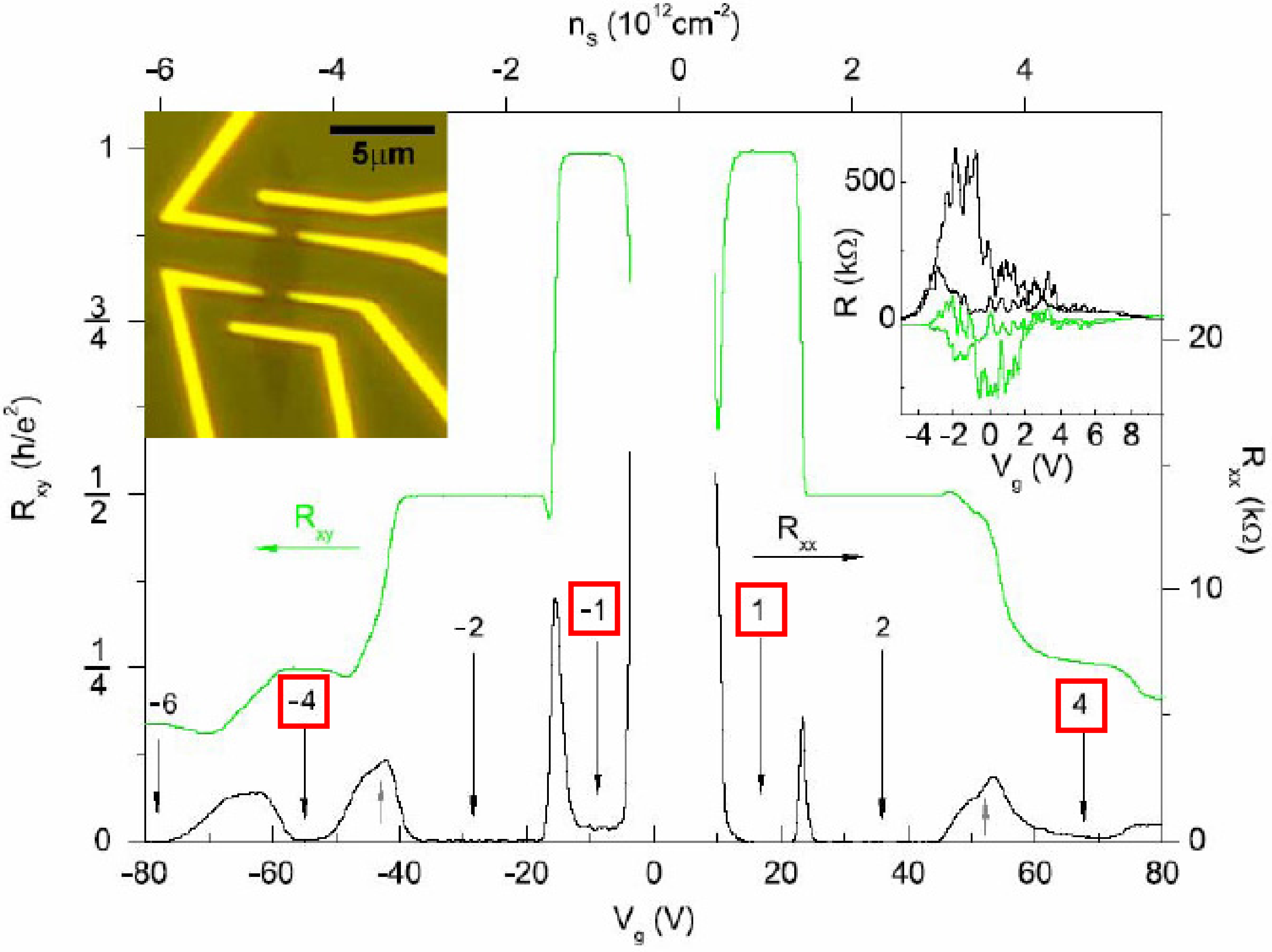
Ripples of graphene on a SiO_2 substrate



Elena Polyakova et al (Columbia Groups), PNAS (2007)

See also Meyer et al, Nature (2007) and Ishigami et al, Nano Letters (2007)

Quantum Hall Effect in Graphene at High Magnetic Field

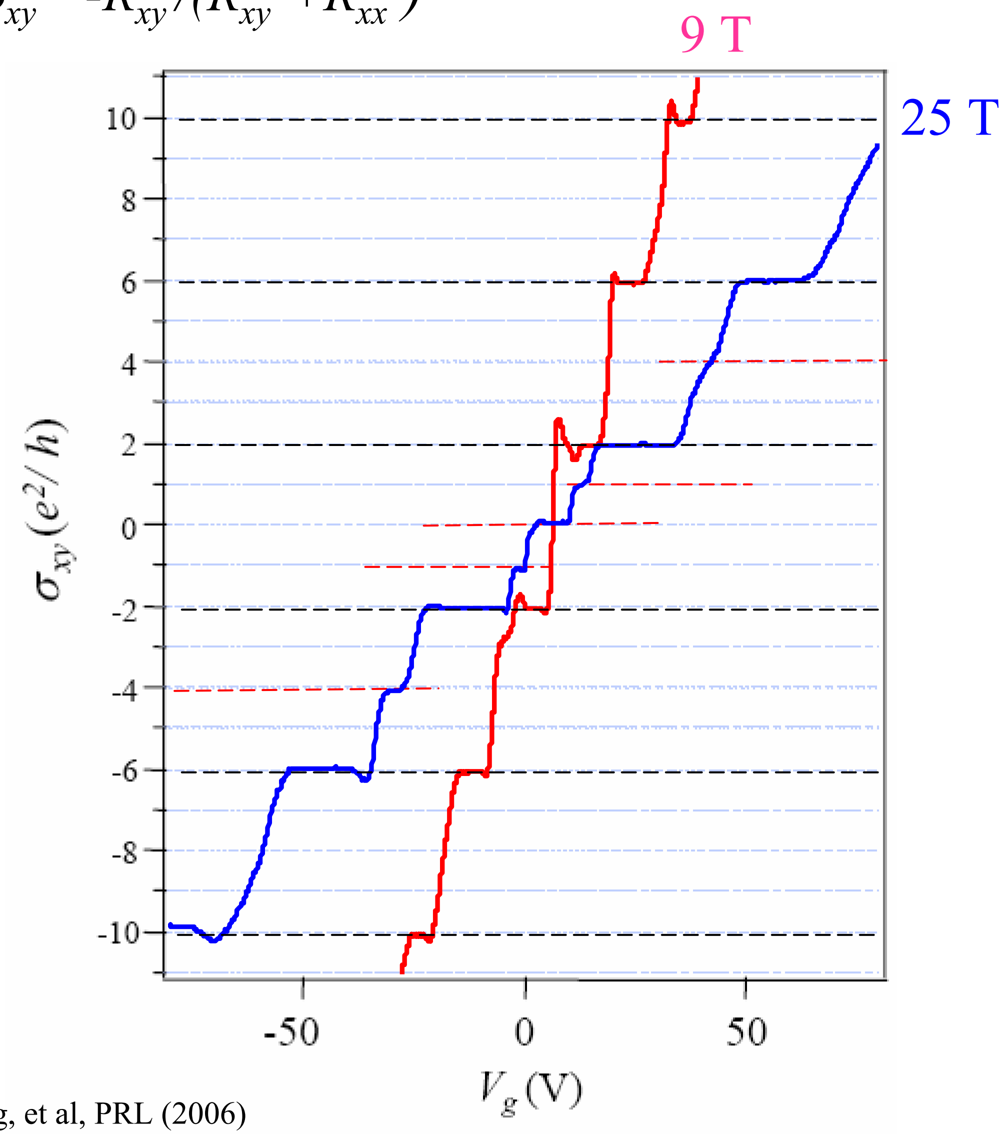


B = 45 T
T = 1.4 K

Zhang, et al, PRL (2006)

Splitting of Landau Levels in High Magnetic Fields

$\sigma_{xy} = -R_{xy}/(R_{xy}^2+R_{xx}^2)$



Zhang, et al, PRL (2006)

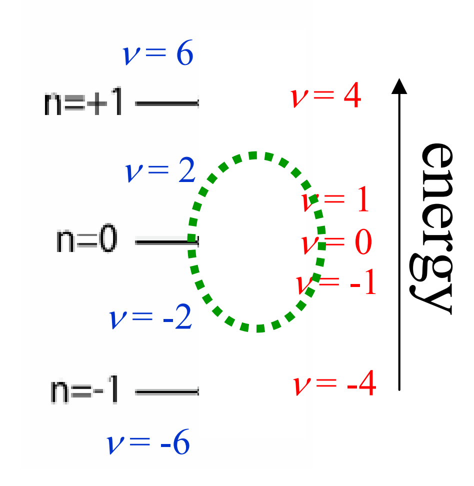
Low fields (B < 10 T)

$\nu = \pm 2, \pm 6, \pm 10, \dots$

High fields (B > 20 T)

$\nu = 0, \pm 1, \pm 2, \pm 4, \pm 6, \dots$

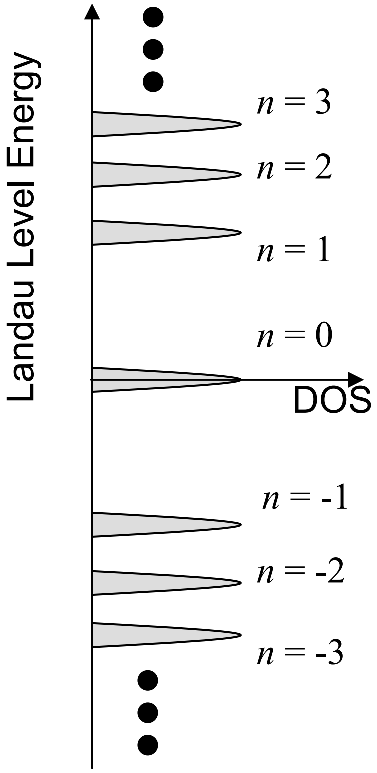
Landau Level $E_n = \mathrm{sgn}(n)\sqrt{2e\hbar v_F^2|n|B}$



Spin & sublattice symmetry lifted!

Quantum Hall Insulator OR Quantum Hall Ferromagnet?

Low magnetic field

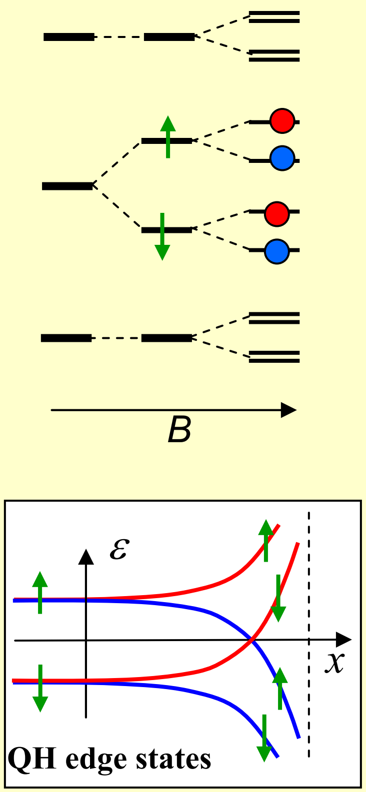


Spin & valley degenerate

High magnetic field degeneracy break: two scenarios

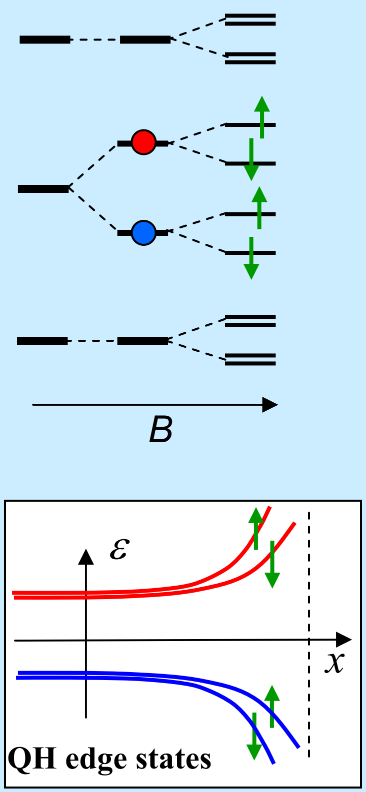
QHE Ferromagnet

Spin -> Pseudo Spin



QHE Insulator

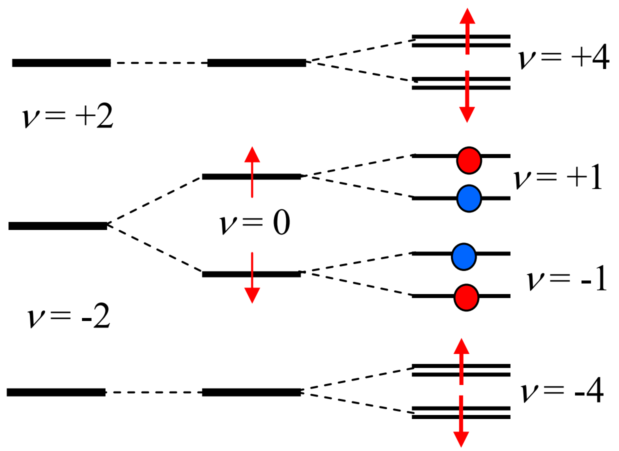
Pseudo Spin -> Spin



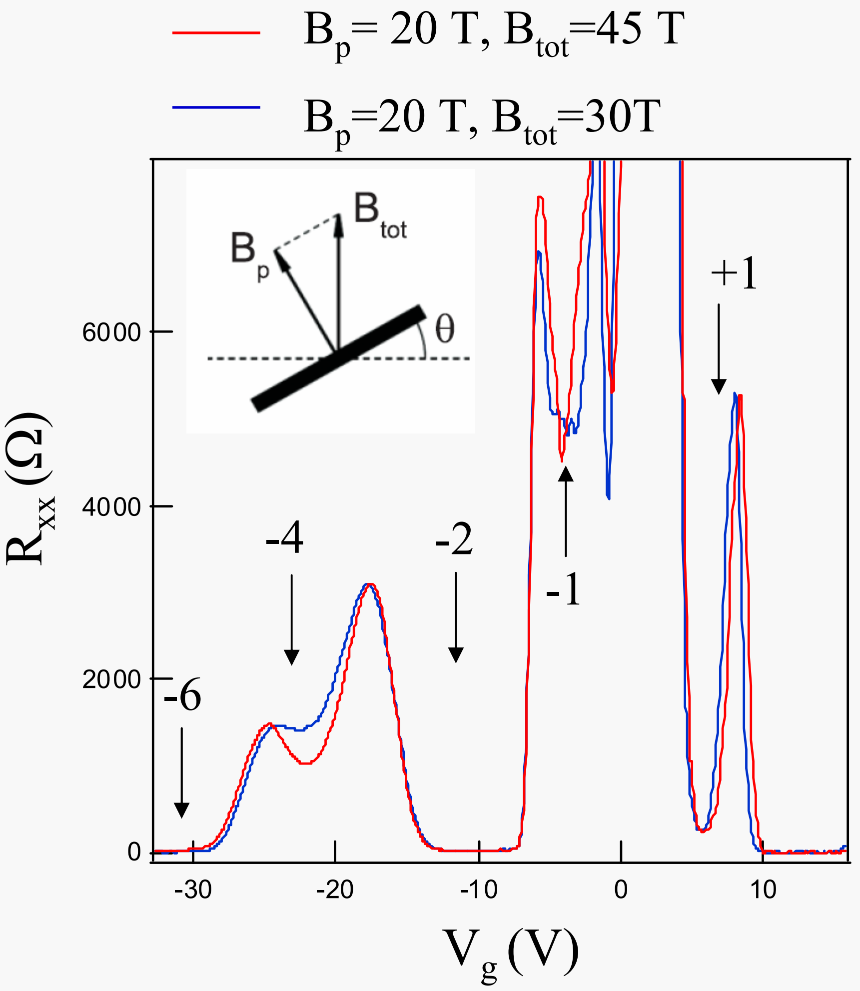
Normura & Macdonald, PRL 96, 256602 (2006); Abanin, Lee, & Levitov, PRL 98, 156801 (2007);

Spin or Pseudo Spin Splitting?

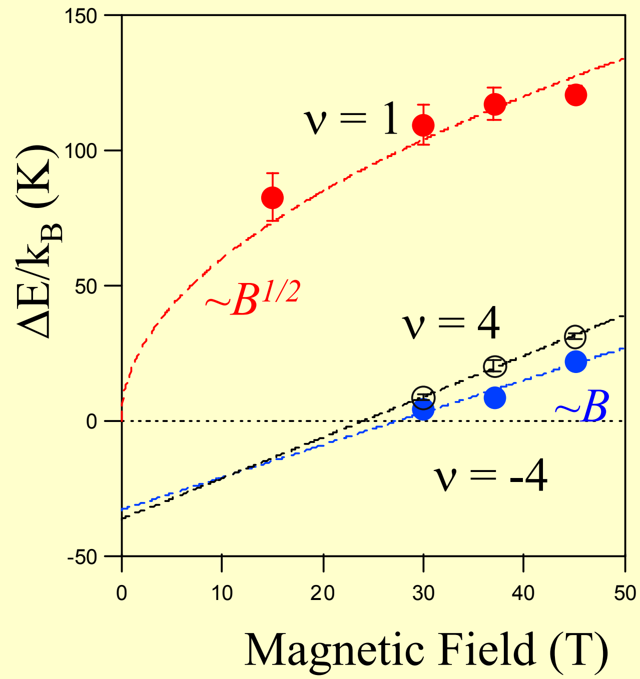
Quantum Hall Ferromaget!



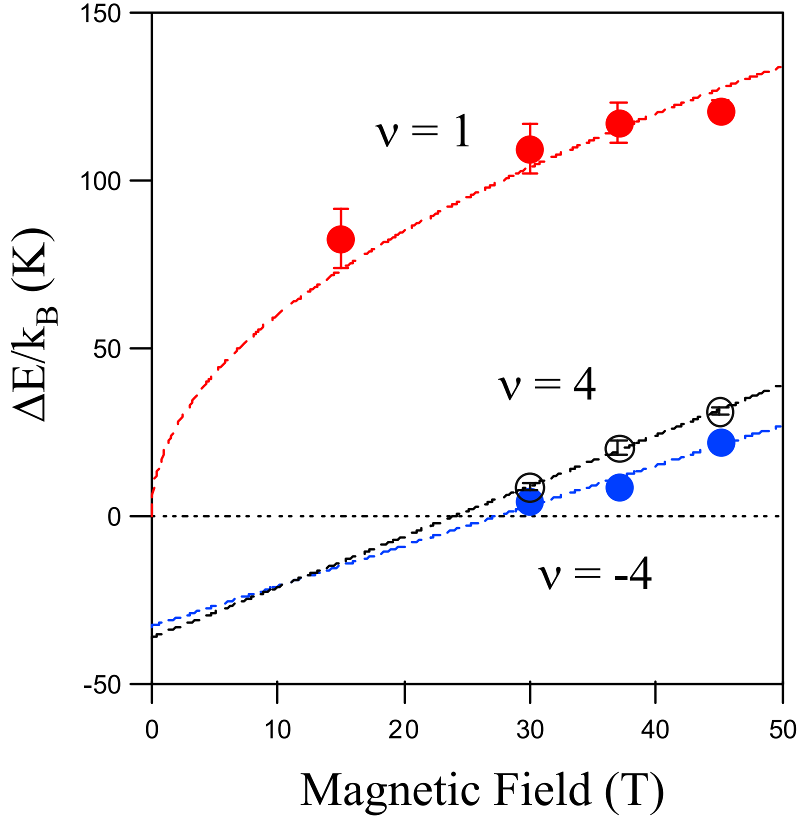
Tilted Magnetic Field



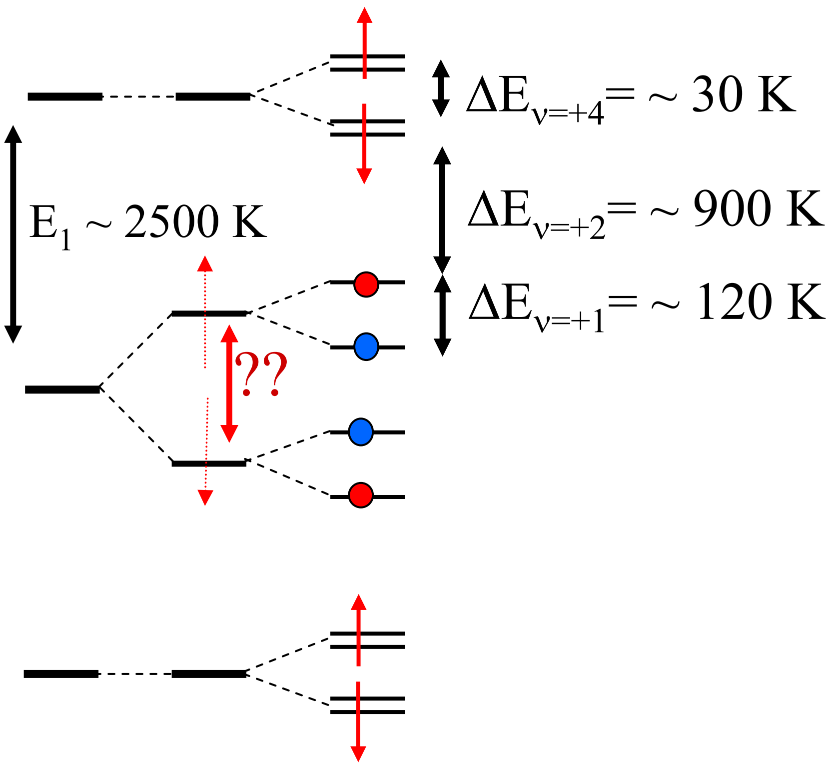
Energy Gap Measurements



Unusual Nature of ν=0 Quantum Hall States: Many-body Origin?



Landau Level Hierarchy



B= 45 T

$\Delta E_{\nu=+4} = \sim 30$ K

$E_1 \sim 2500$ K

$\Delta E_{\nu=+2} = \sim 900$ K

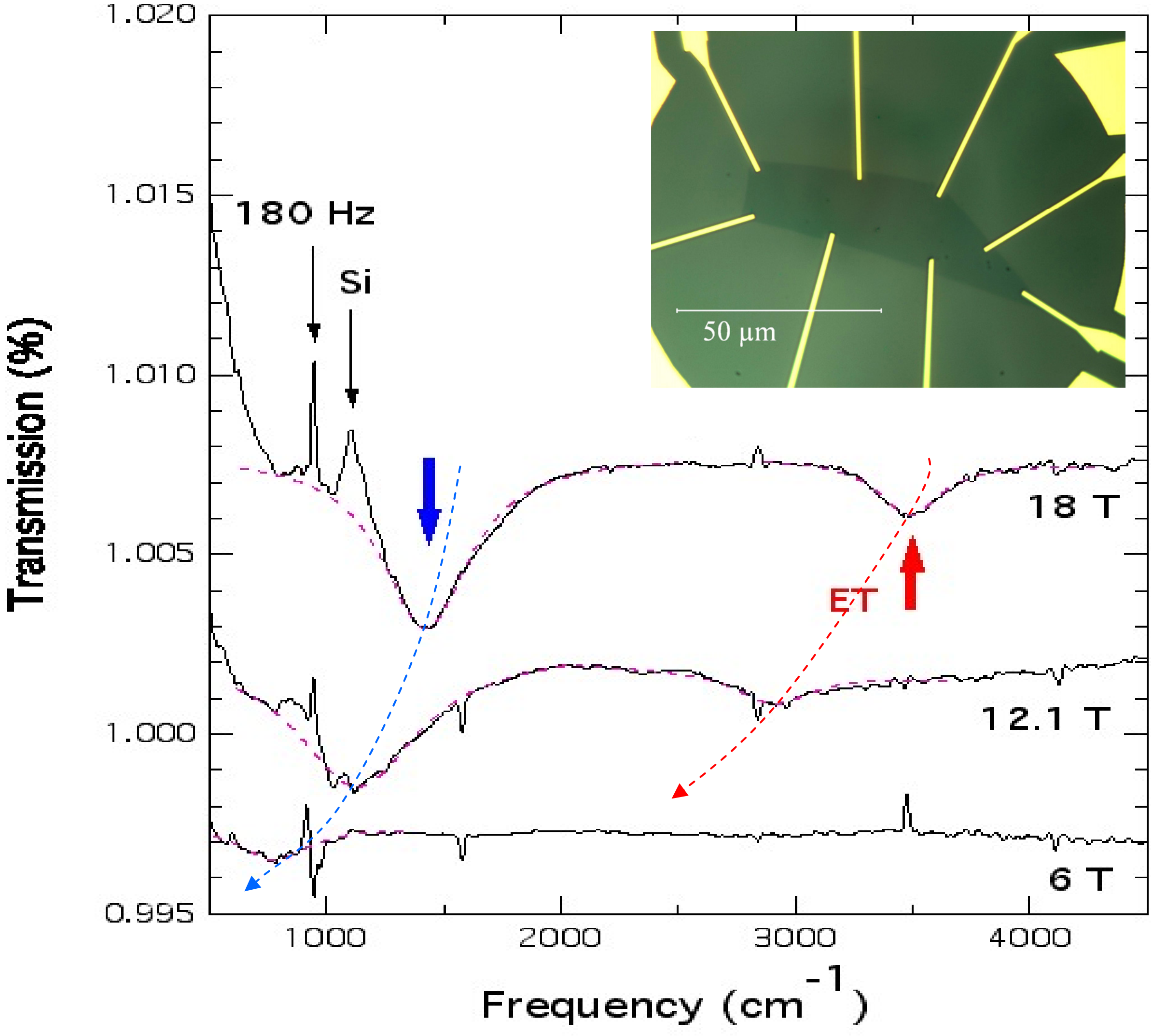
$\Delta E_{\nu=+1} = \sim 120$ K

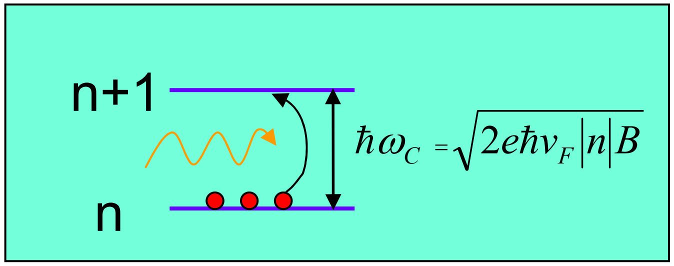
??

* Signature of enhanced e-e interaction near the Dirac point

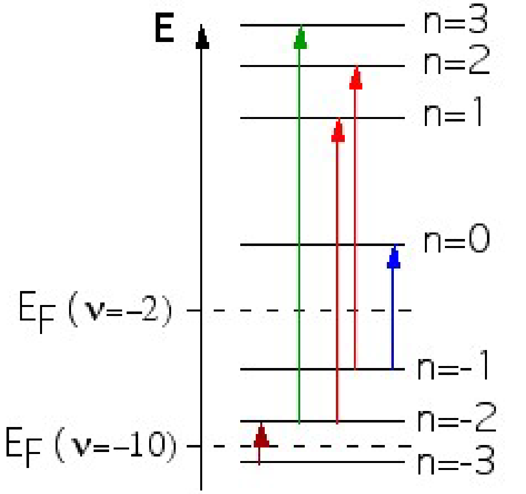
* What is the nature of $\nu = 0$ state?

Energy Gap Measurement: Cyclotron Resonance





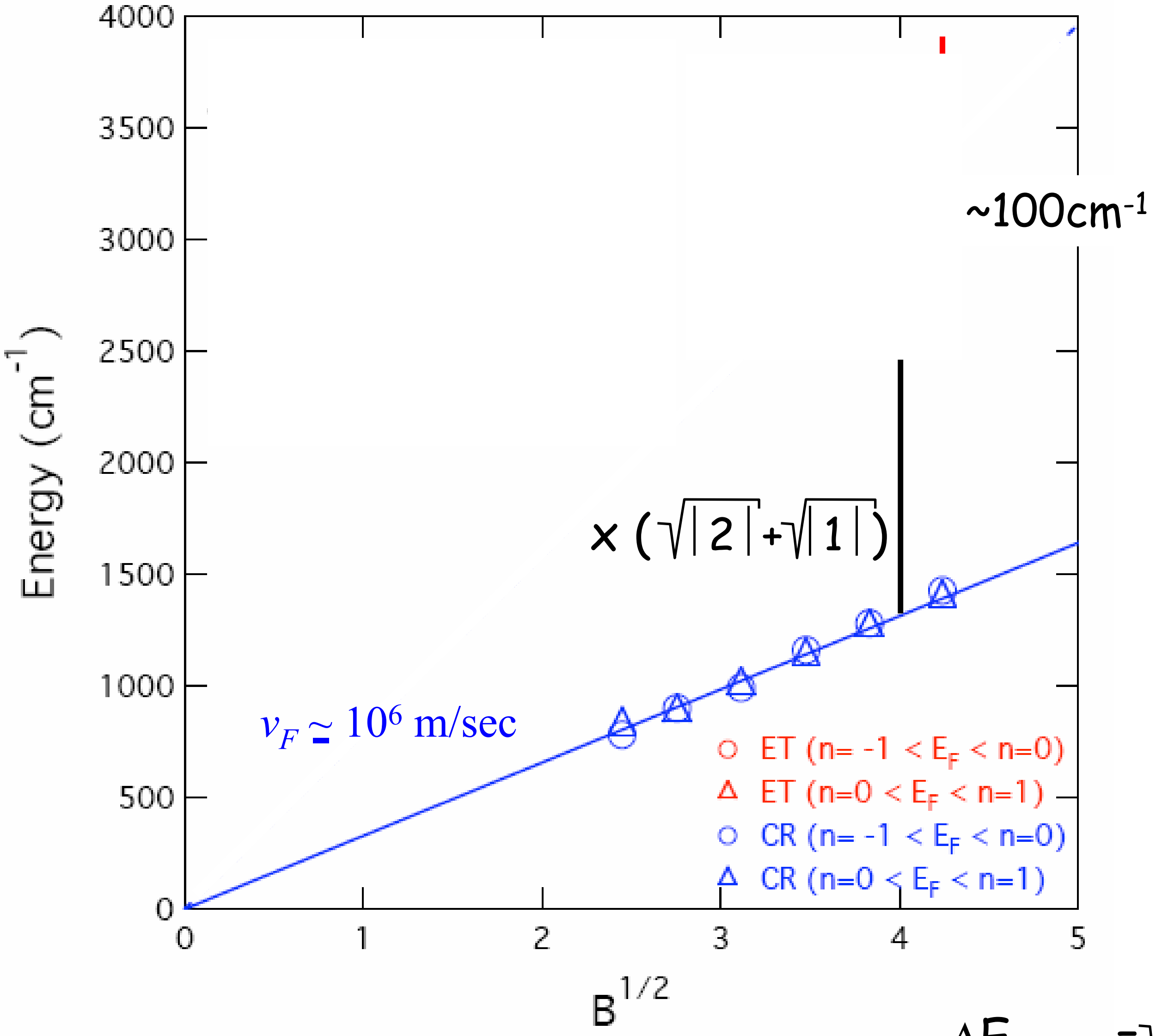
$$\hbar\omega_C = \sqrt{2e\hbar v_F |n| B}$$



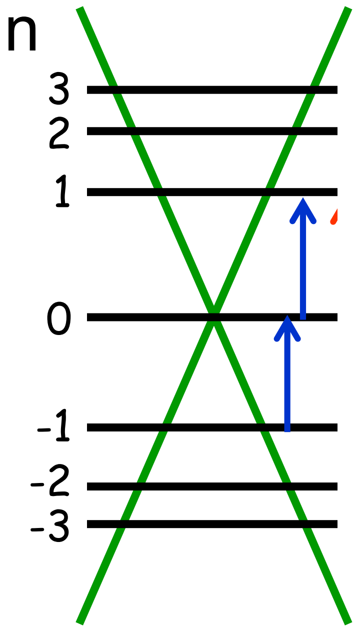
Jiang et al. PRL (2007)

Excitonic Transition: Electron-electron interaction??

e-e interaction is important!



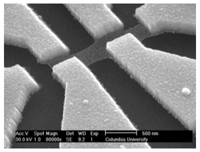
$$E_n = \sqrt{2e\hbar v_F |n| B}$$

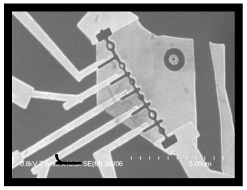


$$\Delta E_{n,\,(n+1)} = \sqrt{2e\hbar v_F B}\,\left(\sqrt{|n+1|} \pm \sqrt{|n|}\right)$$

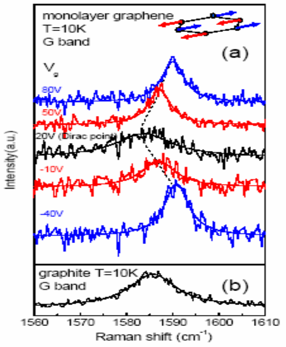
Jiang et al. PRL (2007)

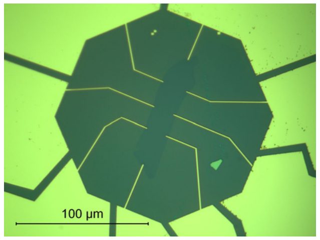
Graphene Research at Columbia University



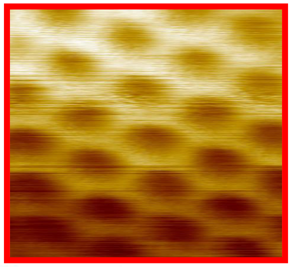


- High Mobility Graphene Samples:
  - Extreme Quantum Limit Transport (Kim +Stormer)
- Graphene Devices
  - Nanostructures, heterostructures, Quantum Interference Devices (Kim)
- Spin Transport in Graphene:
  - Spin Hall Devices, Non-local spin transport devices (Kim)

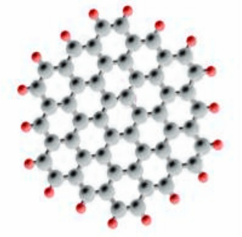




- Graphene for Optical Studies:
  - Raman Spectroscopy (Kim + Pinczuk)
  - Absorption Spectroscopy (Heinz)
- Graphene spectroscopy
  - IR (Kim+Stormer), Photoemission (Osgood)



- STM on graphene:
  - local electronic structure, molecular assembly on graphene (Kim + Flynn)



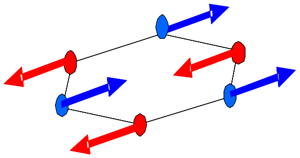
- Graphene Organic Chemistry:
  - Edge decoration, covalent doping in graphene (Kim + Nuckolls)
- Graphene Synthesis and Photochemstry:
  - Low temperature synthesis and surface photochemistry (Brus)
- Graphene Intercalation (O’brien)

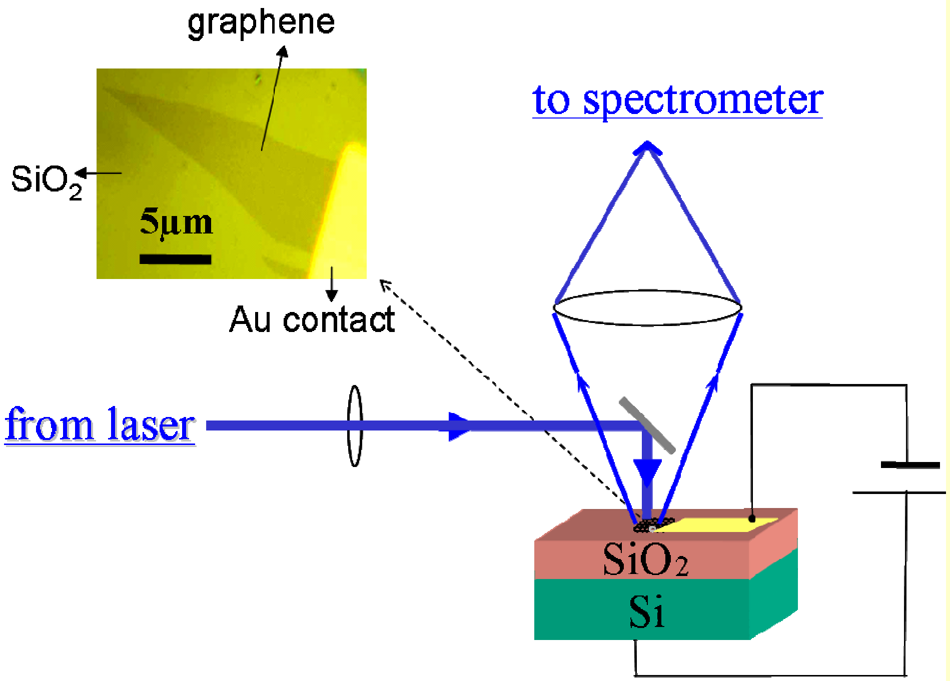
- Graphene Theory: Hybertsen, Millis, Aleiner, Altshuler

Raman Spectroscopy on Graphene: Gate Voltage Dependence

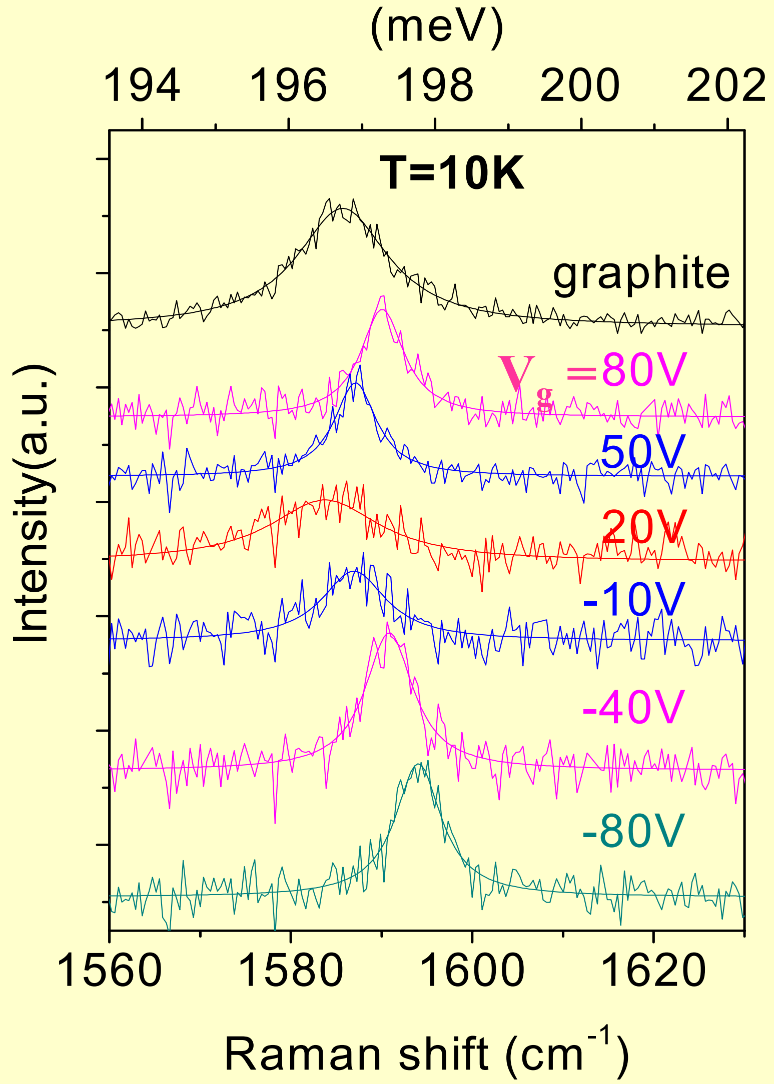
Graphene G-mode phonon

$$\hbar w_G \approx 200\, meV, \quad \vec{k} = 0$$





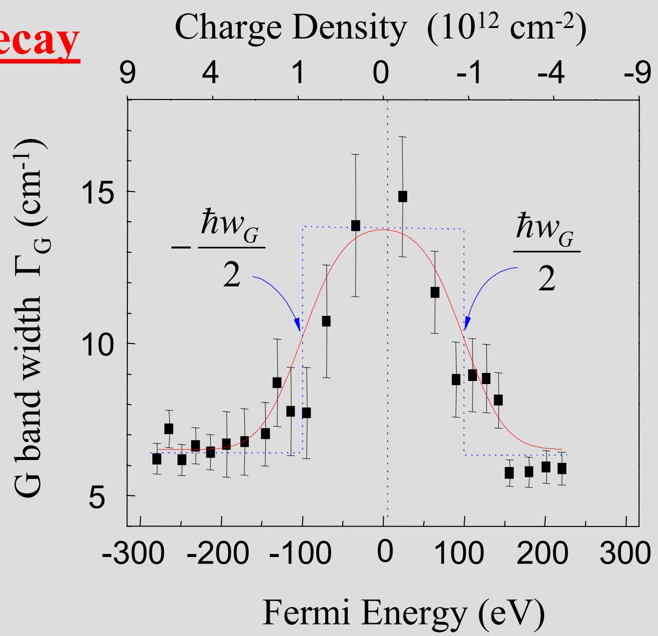
Raman G band



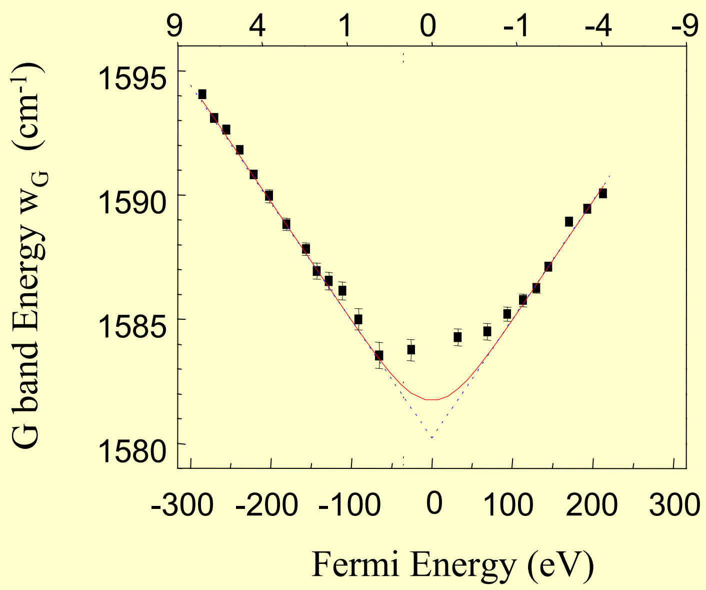
J. Yan, Y. Zhang, P. Kim and A. Pinczuk (2006)

Raman Spectroscopy on Graphene: Gate Voltage Dependence

Phonon Decay



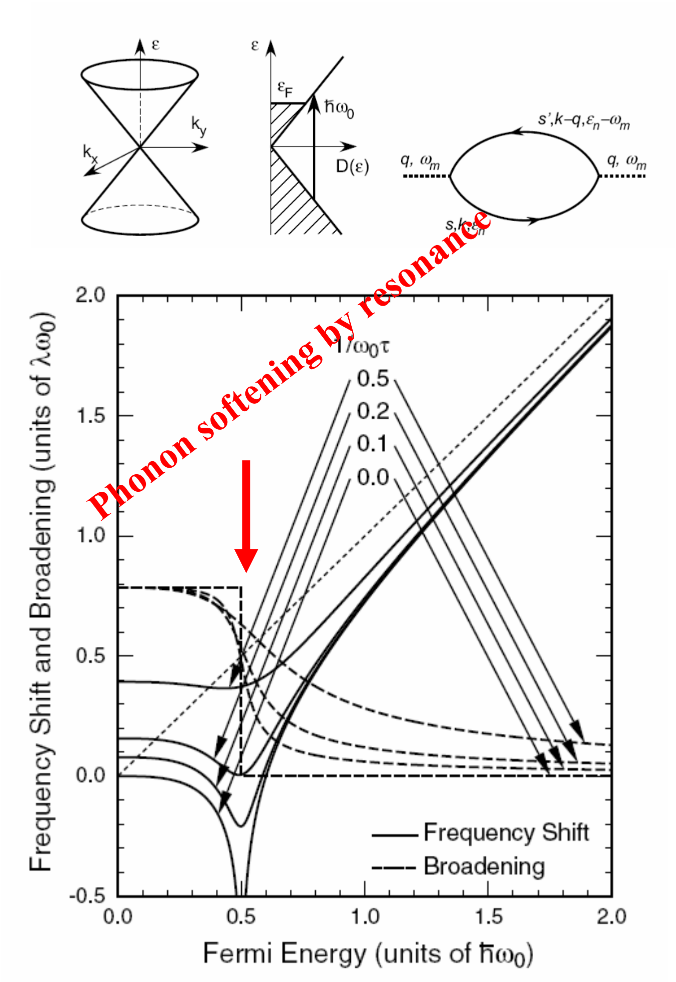
Renormalization



J. Yan, Y. Zhang, P. Kim and A. Pinczuk (2006); See also Ferrari et al (2006)

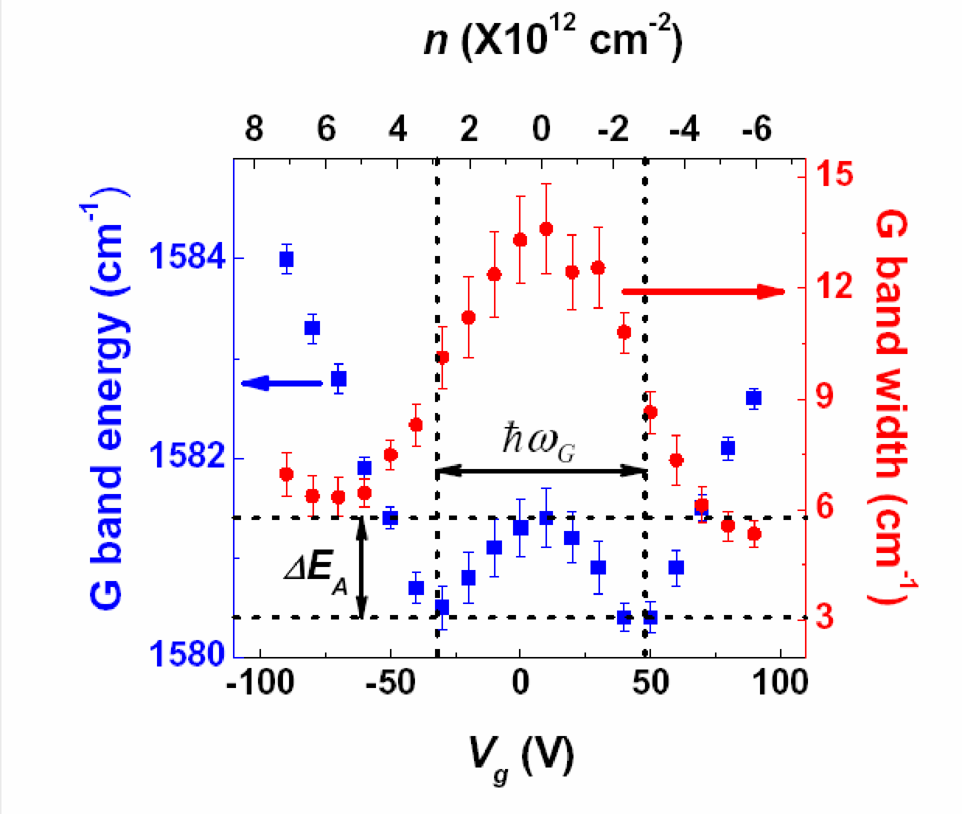
Unusual Phonon Softening in Bi-Layer Graphene

T. Ando, J. Phys. Soc. Jpn. (2006)



Phonon softening by resonance

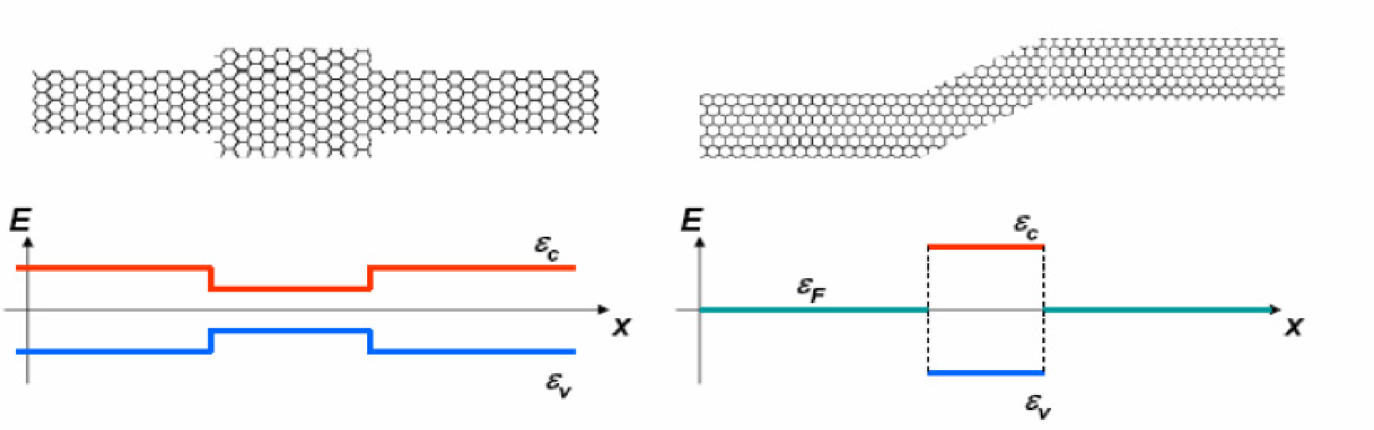
G band Raman Spectrum in Bilyaer Graphene



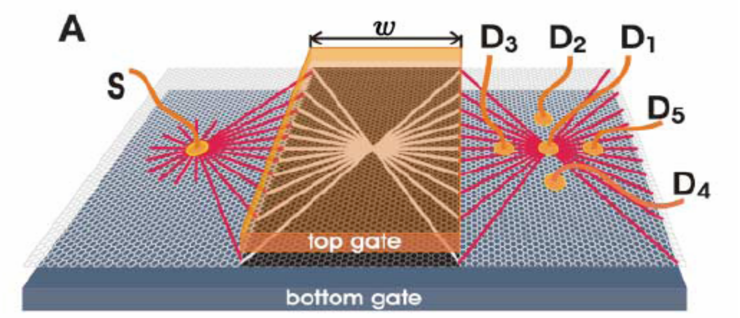
Yan, Henriksen, Kim and Pinczuk (2007)

Graphene Electronics

Engineers' Dreams

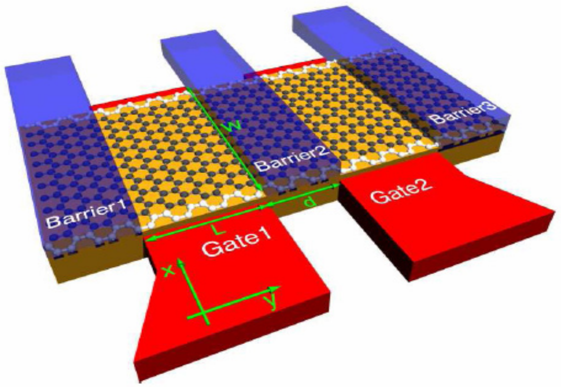


Theorists' Dreams



Graphene Veselago lense

Cheianov *et al. Science* (07)

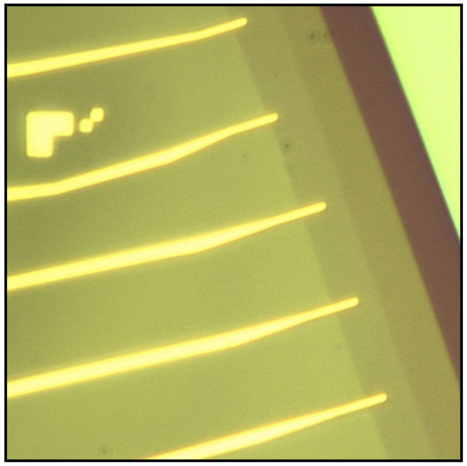


Graphene q-bits

Trauzettel *et al. Nature Phys.* (07)

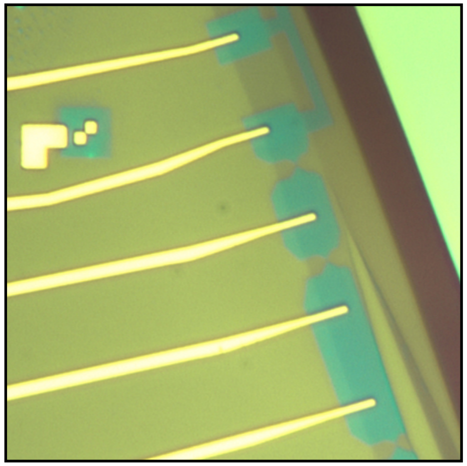
and
more …

From Graphene “Samples” To Graphene “Devices”



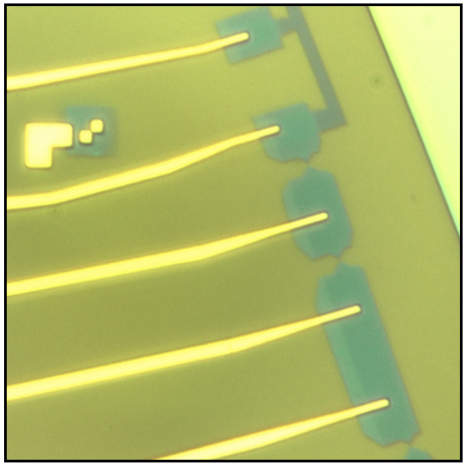
Contacts:

PMMA
EBL
Evaporation



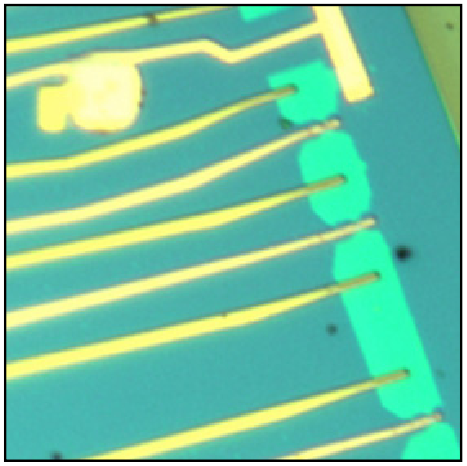
Graphene patterning:

HSQ
EBL
Development



Graphene etching:

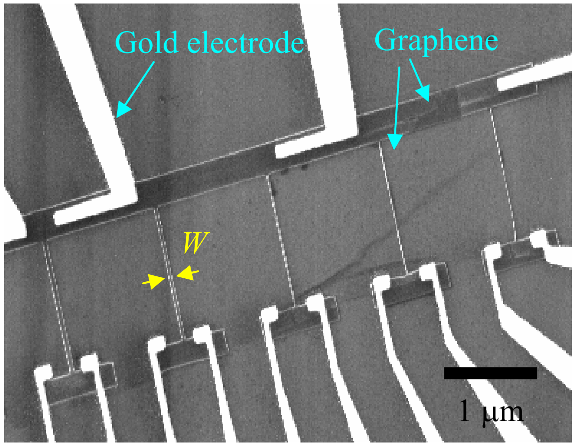
Oxygen plasma



Local gates:

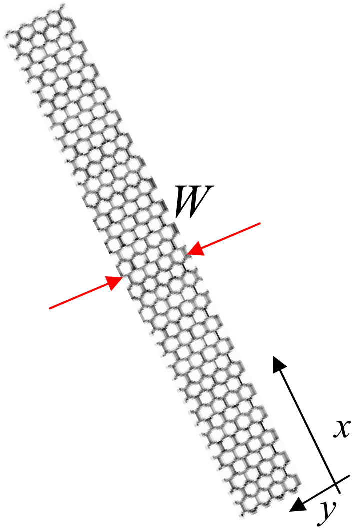
ALD HfO_2
EBL
Evaporation

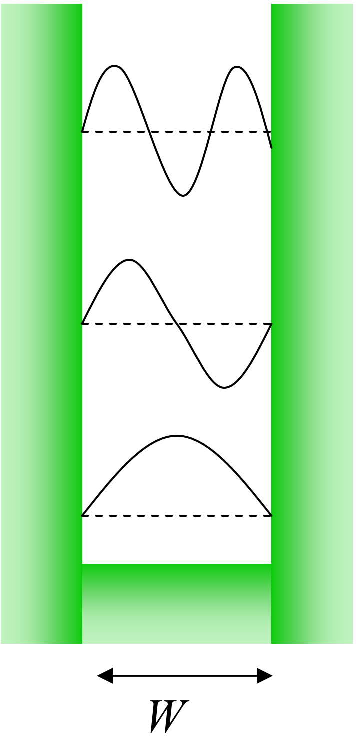
Graphene Nanoribbons: Confined Dirac Particles



10 nm < *W* < 100 nm

Dirac Particle Confinement





$$k_y = \frac{3\cdot\pi}{W}$$

$$k_y = \frac{2\cdot\pi}{W}$$

$$k_y = \frac{1\cdot\pi}{W}$$

$$\Delta k_y = \frac{\pi}{W}$$

$$E = \pm\hbar v_F \sqrt{k_x^{\,2} + (\pi n / W)^2}$$

$$E_{\text{gap}} \sim \hbar v_F \Delta k \sim h v_F / W$$

Graphene nanoribbon theory partial list

K. Nakada, M. Fujita, G. Dresselhaus, M. S. Dresselhaus, Phys. Rev. B **54**, 17954 (1996).
K. Wakabayashi, M. Fujita, H. Ajiki, M. Sigrist, Phys. Rev. B **59**, 8271 (1999).
Y. Miyamoto, K. Nakada, M. Fujita, Phys. Rev. B **59**, 9858 (1999).
M. Ezawa, Phys. Rev. B **73**, 045432 (2006).
N. M. R. Peres, A. H. Castro Neto, and F. Guinea, Phys. Rev. B **73**, 195411 (2006)
L. Brey and H. A. Fertig, Phys. Rev. B **73**, 235411 (2006).
Y. Ouyang, Y. Yoon, J. K. Fodor, and J. Guo, Appl. Phys. Lett. **89**, 203107 (2006).
Y.-W. Son, M. L. Cohen, S. G. Louie, Nature **444**, 347 (2006)
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V. Barone, O. Hod, G. E. Scuseria, Nano Lett **6** 2748 (2006).
D. A. Areshkin, D. Gunlycke, C. T. White, Nano Lett. **7**, 204 (2007).

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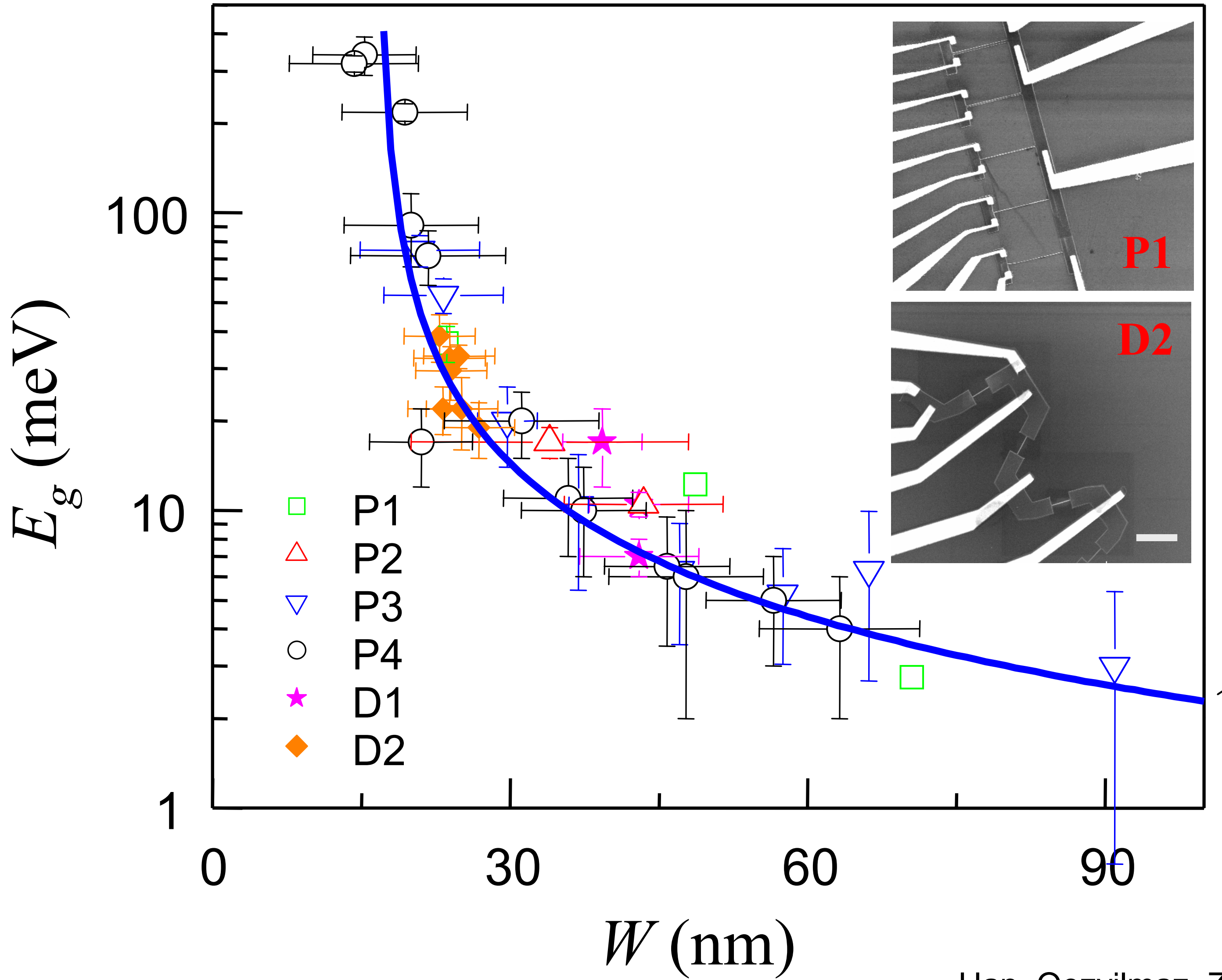
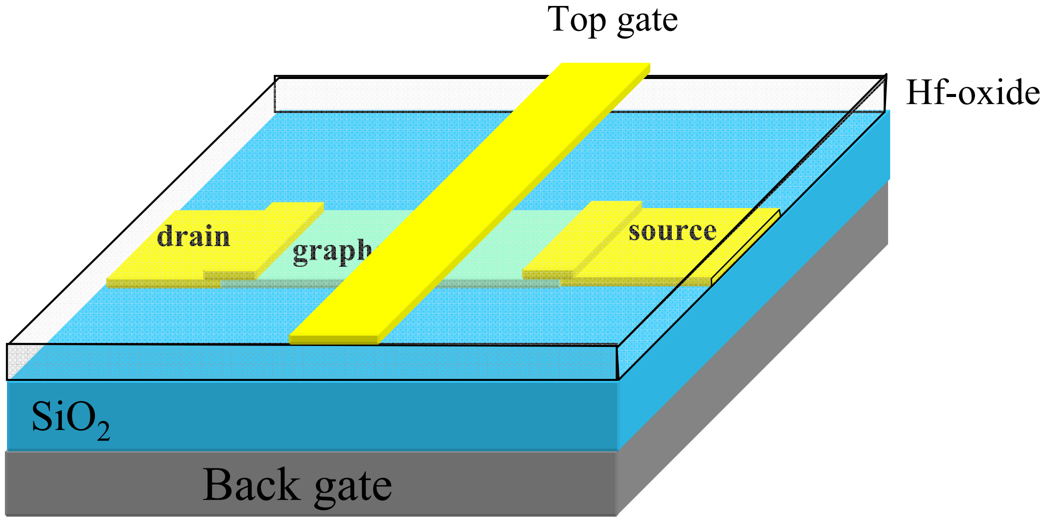
Scaling of Energy Gaps in Graphene Nanoribbons



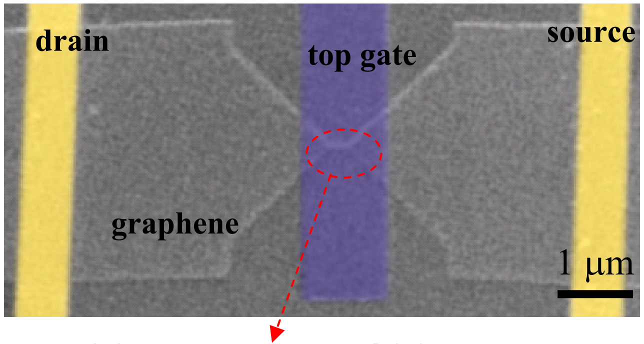
$E_g = E_0/(W-W_0)$

Han, Oezyilmaz, Zhang and Kim PRL (2007)

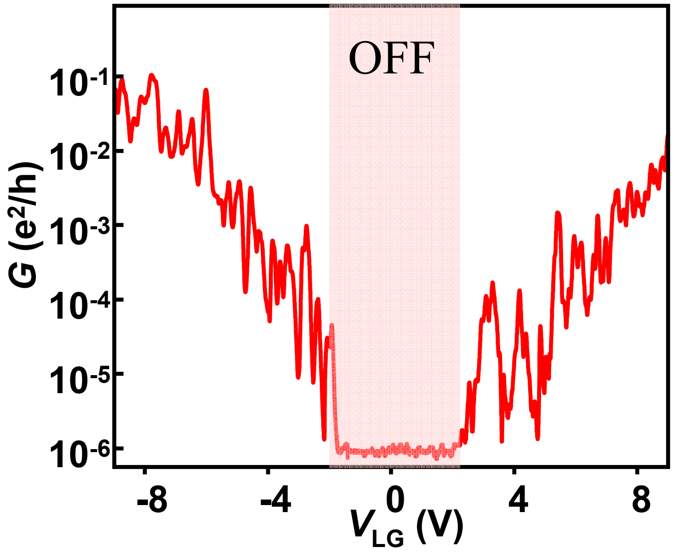
Top Gated Graphene Nano Constriction

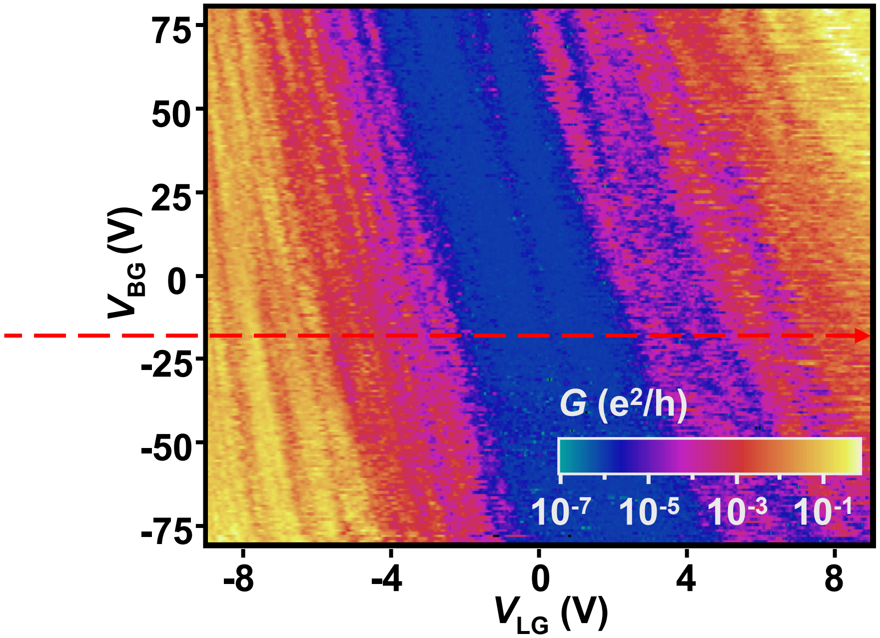


SEM image of device



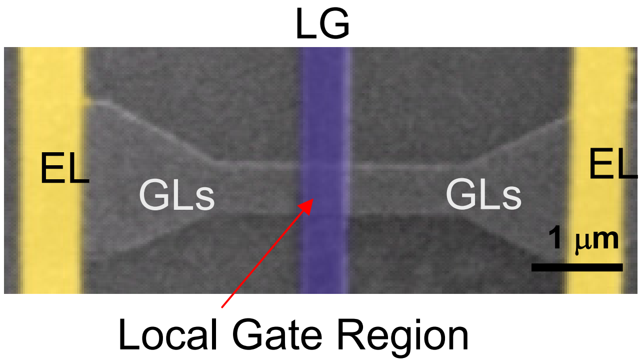
30 nm wide x 100 nm long

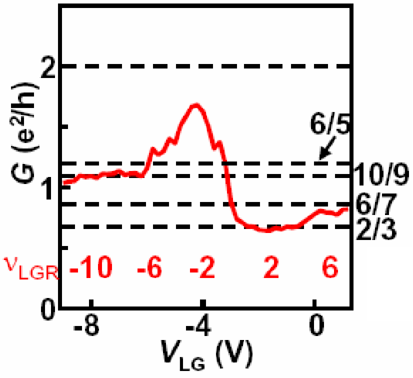


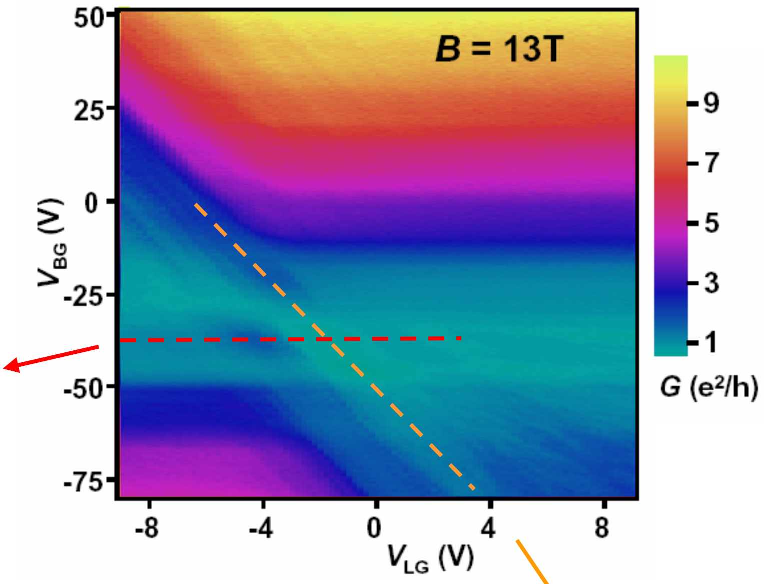


Oezyilmaz, et al., APL (2007)

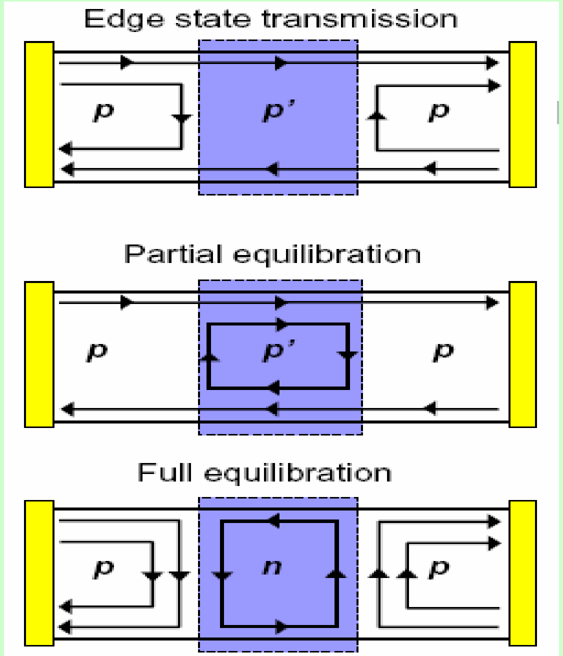
Graphene Quantum Hall Edge State Conduction

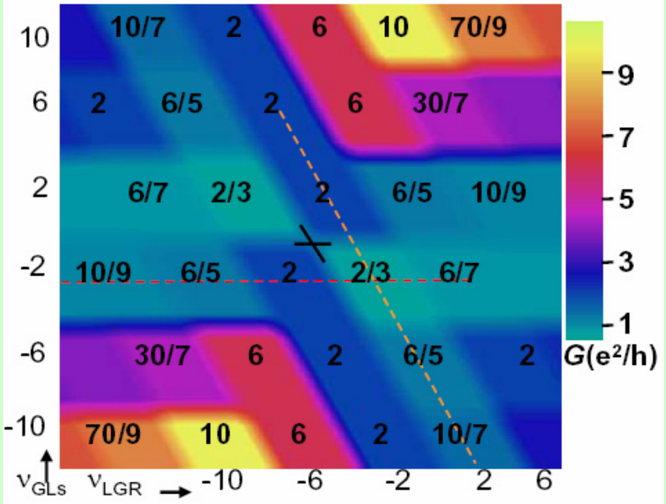


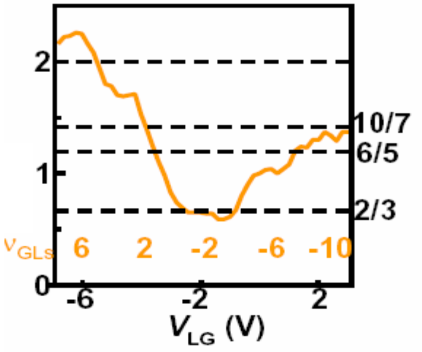




simple model (following Haug *et al*)





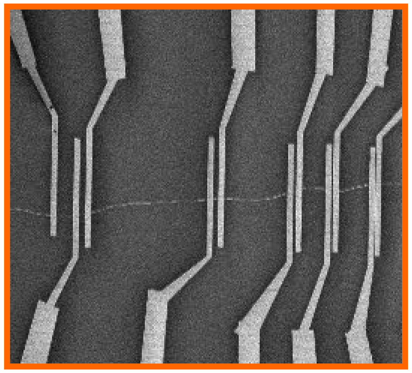


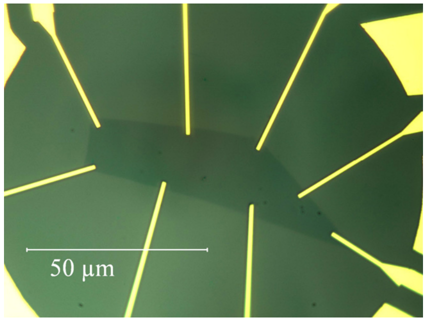
Oezyilmaz, et al., PRL (2007) See also Related work by Williams *et al.* Science (2007)

Summary

Graphitic Carbon Systems

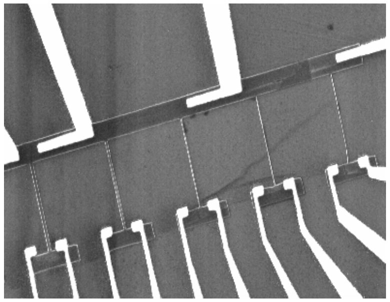
- Zero effective mass, Zero gap
- Pseudo spin
- Extremely Long Mean Free Path in Nanotubes
- Unusual quantum Hall effect in Graphene





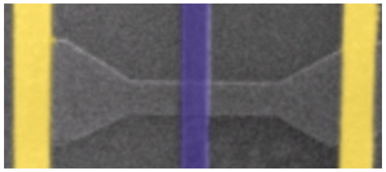
Strong Correlation in Graphene

- e-e interaction
- strongly correlated behavior near the Dirac points



Graphene Electronic Devices

- Band Gap Engineering in graphene nanostructures
- Local density control of graphene
- Peculiar quantum Hall edge states



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Dmitri Efetov
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Namdong Kim
Barbaros Oezyilmaz
Kirill Bolotin
Pablo Jarrilo-Herrero
Zhigang Jiang

Collaboration:

Stormer, Pinczuk, Heinz, Uemura, Venkataraman, Nuckolls, Brus, Flynne, Hone, KS Kim, GC Yi

Kim Group: 2007
Roof top of Pupin Laboratory

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FENA