Graphene: Experimental Overview

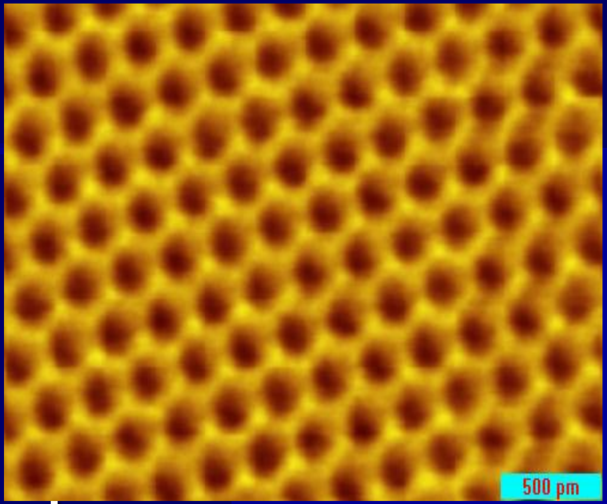
10^3 papers

Eva Y. Andrei

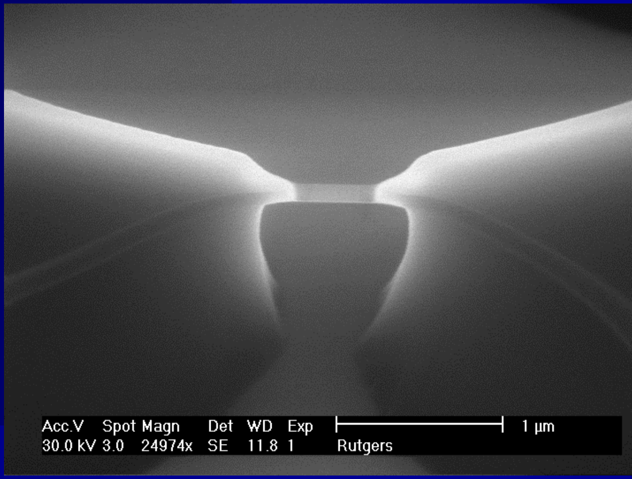
Rutgers University

Nobel Symposium – Stockholm May 2010

Graphene: An Experimental overview



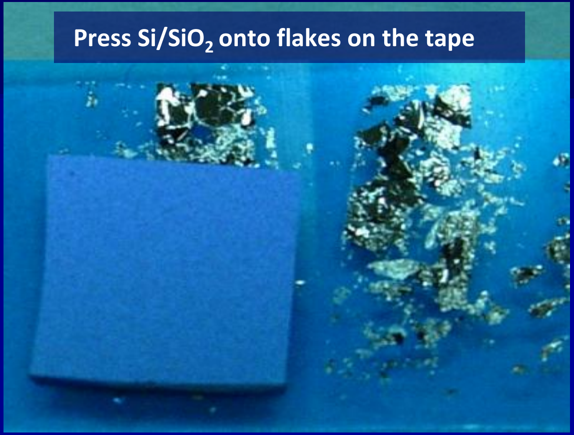
- Making graphene
- Gee Wizz experiments
- Graphene decoupled from substrate
  - Graphene on graphite
  - Suspended graphene

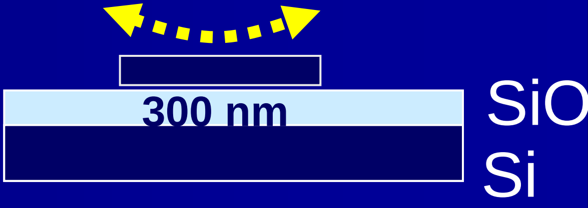


Making Graphene

Exfoliation

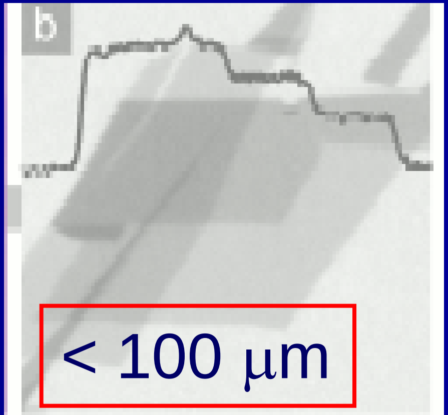

Scotch tape with graphite flakes


Press Si/SiO$_2$ onto flakes on the tape



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]

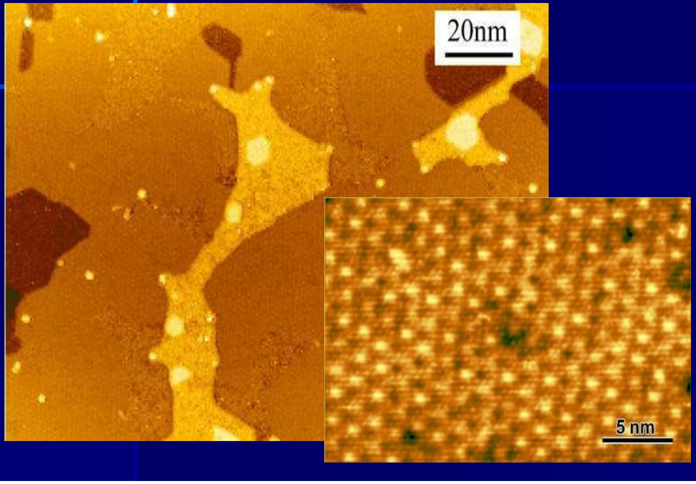


Novoselev et al Science (2004)

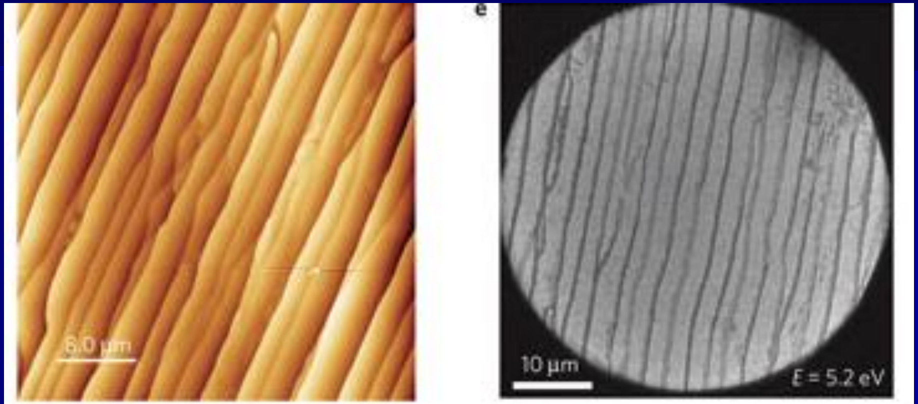
Making Graphene

Graphitization

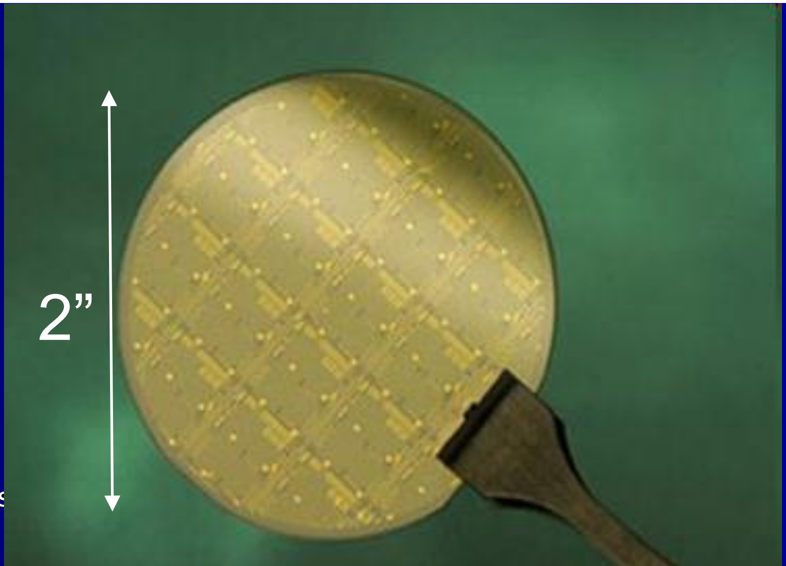
Epitaxial grapehene on SiC



Epitaxial graohene
W. A. de Heer et al (2007)
C. Berger, et al J. Phys. Chem.B 108 (52) (2004)



Towards wafer-size graphene layers by atmospheric pressure graphitization of silicon carbide
K. V. Emtsev , et al Nature materials *(2009)*



2009 IEEE

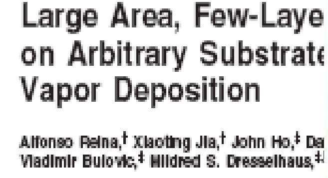
Epitaxial Graphene Growth on SiC Wafers

D.K. Gaskill et al .

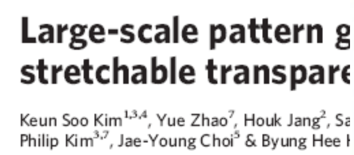
Making Graphene

Chemical Vapor Deposition

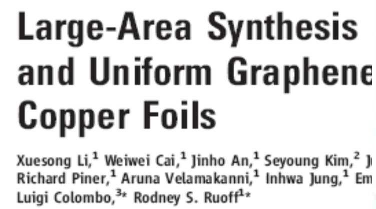
Epitaxial grapehene on metals Ir, Ru, Ni, Cu


Large Area, Few-Laye
on Arbitrary Substrate
Vapor Deposition

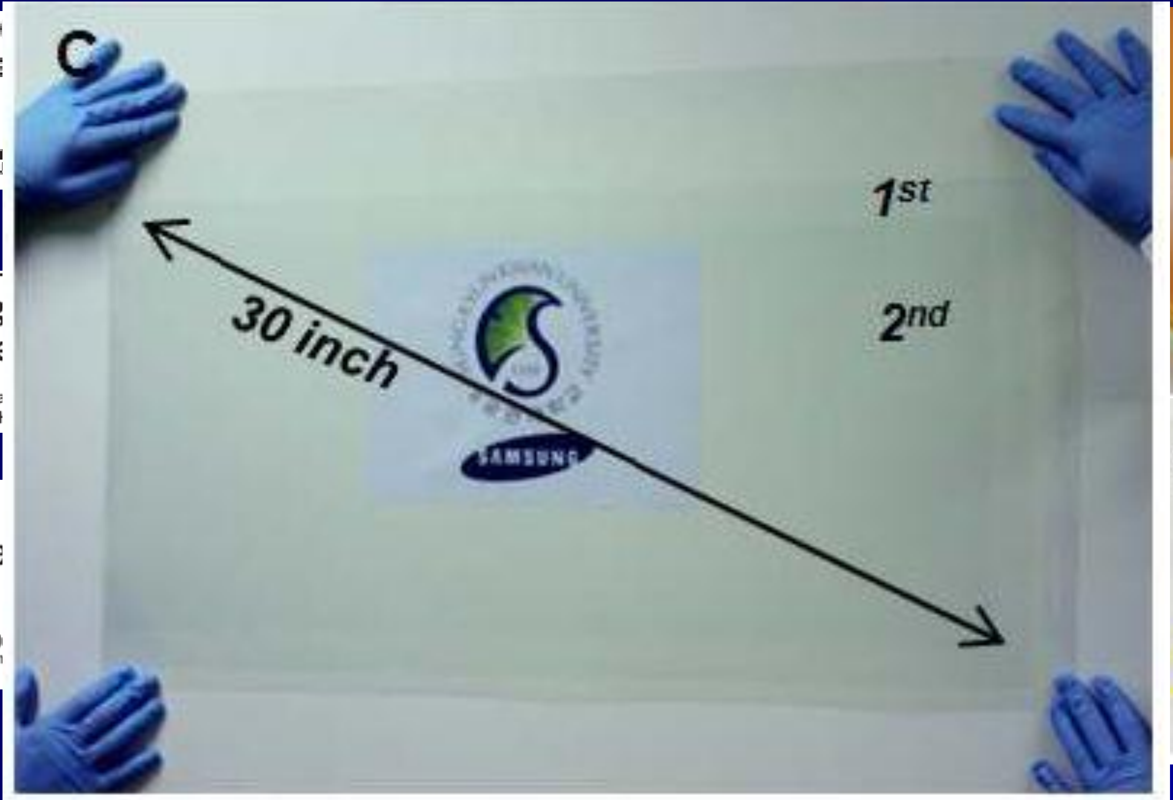
Alfonso Reina,[†] Xiaoting Jia,[†] John Ho,[‡] Da
Vladimir Bulovic,[‡] Mildred S. Dresselhaus,[‡]

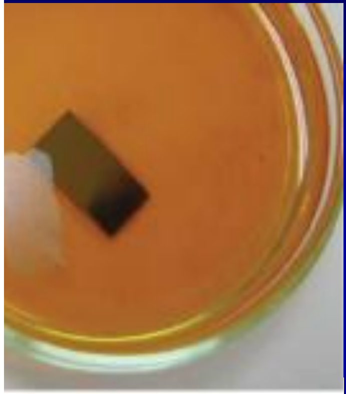

Large-scale pattern g
stretchable transpare

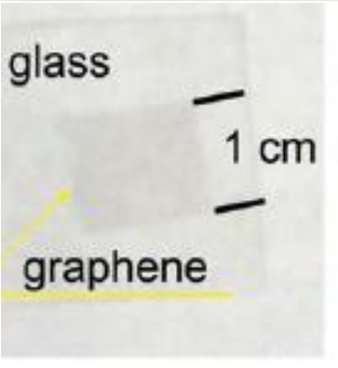
Keun Soo Kim[1,3,4], Yue Zhao[7], Houk Jang[2], Sa
Philip Kim[3,7], Jae-Young Choi[5] & Byung Hee H

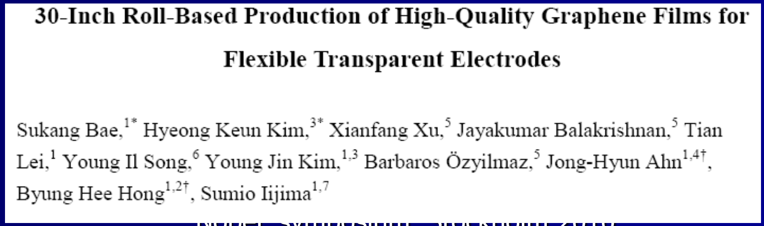

Large-Area Synthesis
and Uniform Graphene
Copper Foils

Xuesong Li,[1] Weiwei Cai,[1] Jinho An,[1] Seyoung Kim,[2] J
Richard Piner,[1] Aruna Velamakanni,[1] Inhwa Jung,[1] Em
Luigi Colombo,[3*] Rodney S. Ruoff[1*]



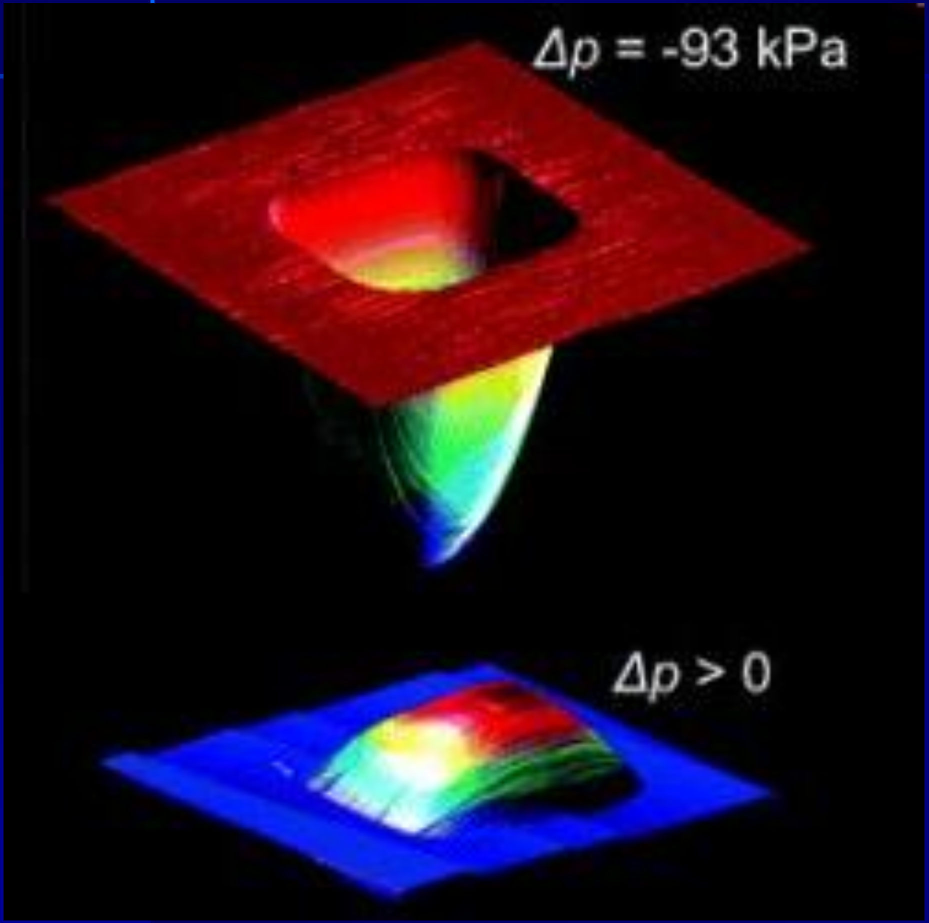




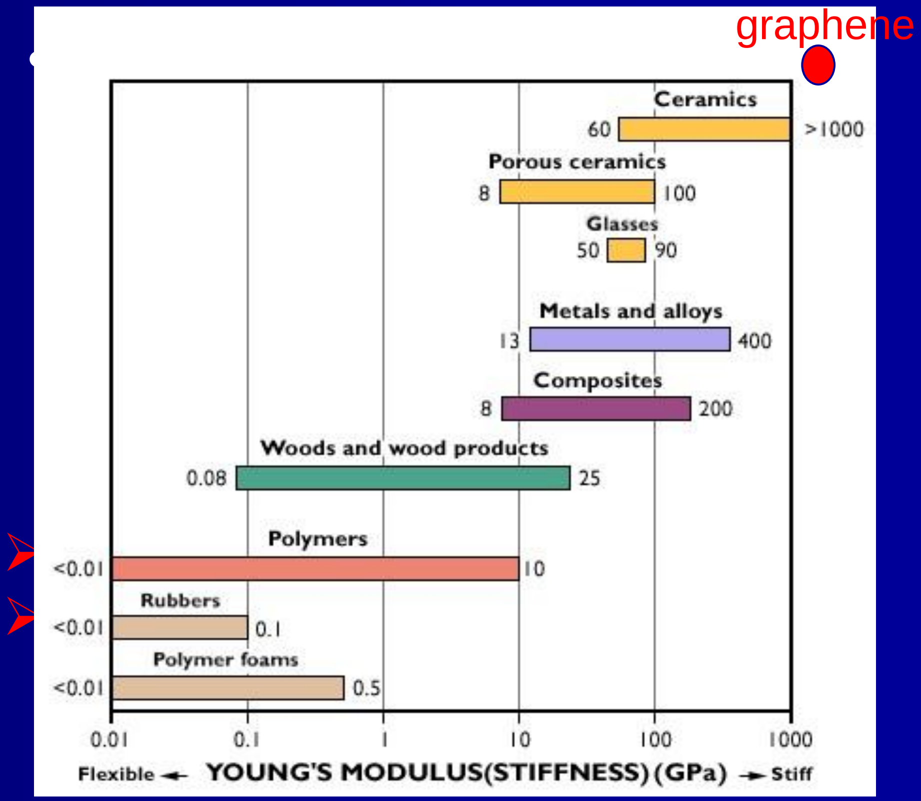

30-Inch Roll-Based Production of High-Quality Graphene Films for Flexible Transparent Electrodes

Sukang Bae,[1*] Hyeong Keun Kim,[3*] Xianfang Xu,[5] Jayakumar Balakrishnan,[5] Tian Lei,[1] Young Il Song,[6] Young Jin Kim,[1,3] Barbaros Özyilmaz,[5] Jong-Hyun Ahn[1,4†], Byung Hee Hong[1,2†], Sumio Iijima[1,7]

Gee Wizz: Mechanical



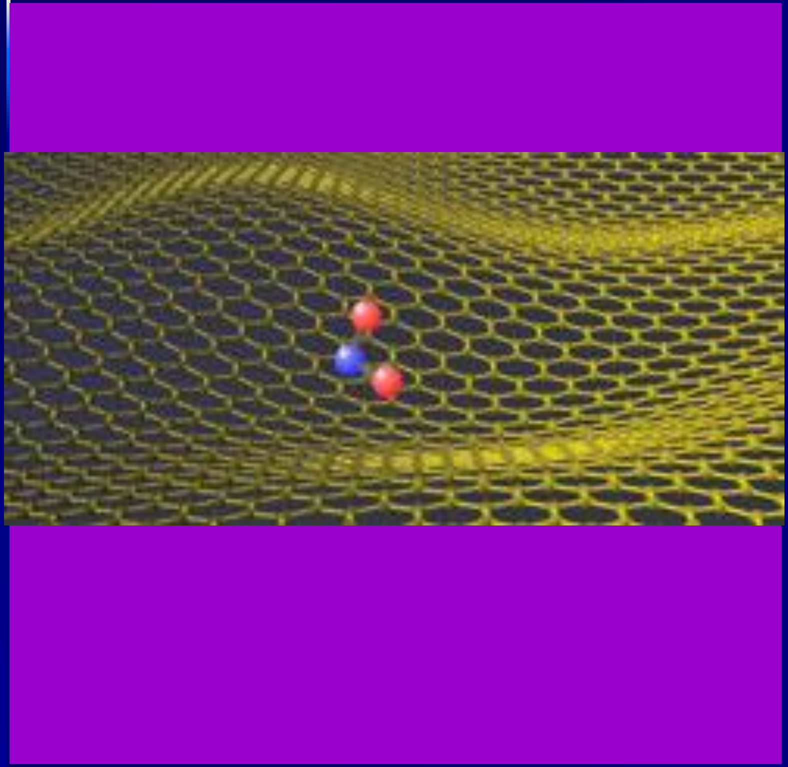
- Young’s modulus ~ 1 TPa

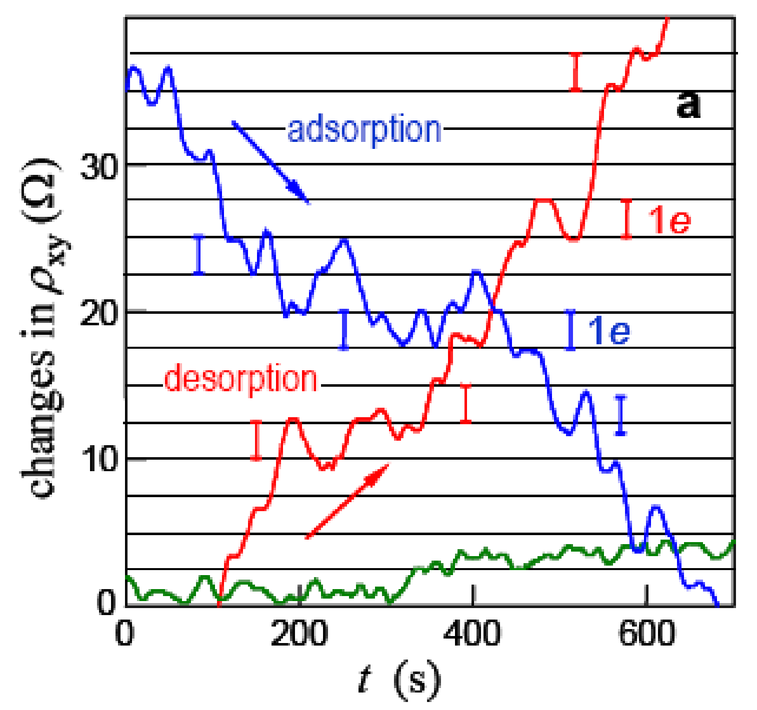


S. Bunch et al,Nano Letters‘08

Gee Wizz: Chemical

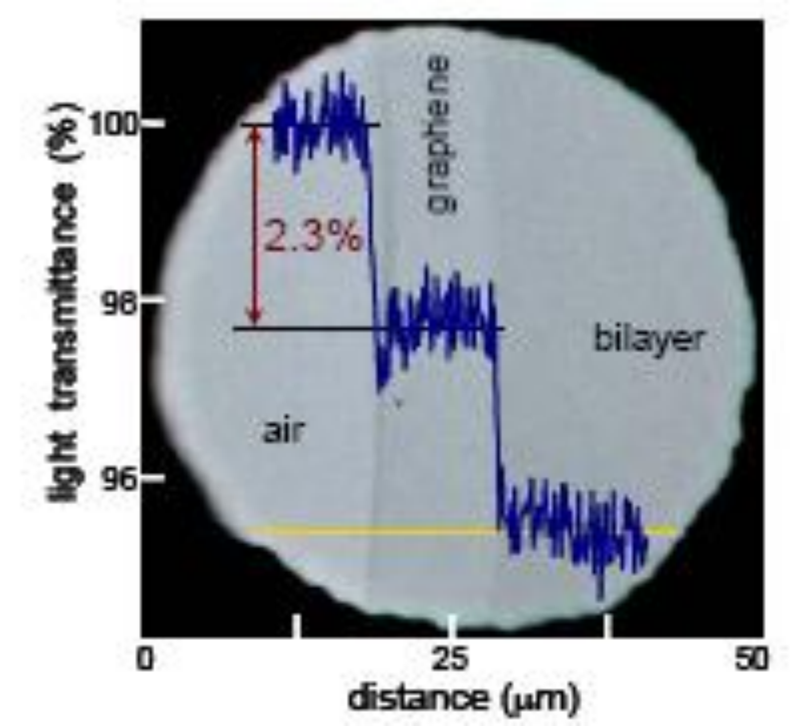
Single molecule detection
NO_2, NH_3, CO





F Schedin *et al*,*Nature Materials* '07

Gee Wizz: Optical

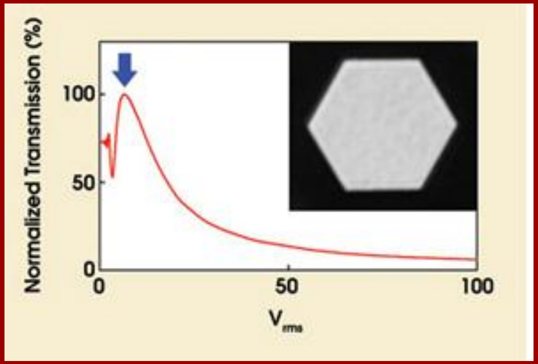


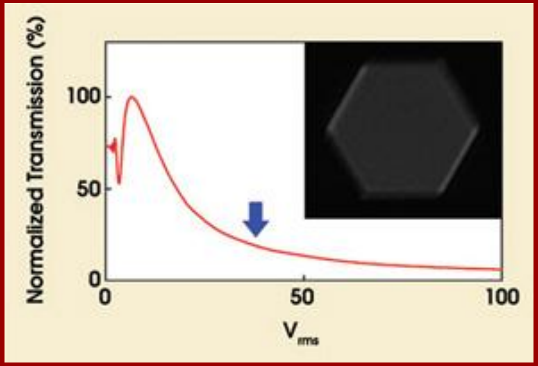
Transmittance at Dirac point:

$$T=1-\alpha\pi=97.2\%$$

R.R. Nair et al, Science (2008).

Graphene layers change their opacity when a voltage is applied,



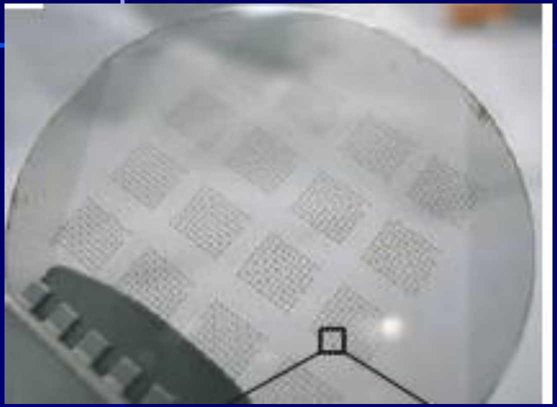


P. Blake *et al*, *Nano Letters*, '08

What is it good for?

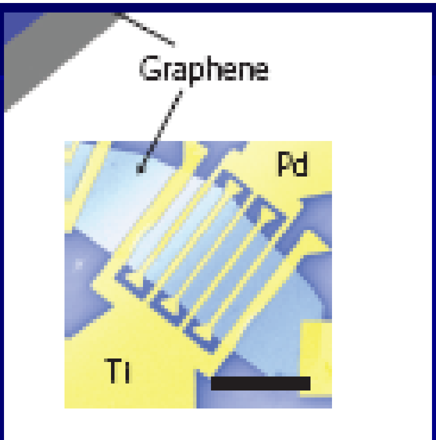
100-GHz Transistors from Wafer-Scale Epitaxial Graphene

Y. M. Lin et al Science 2010



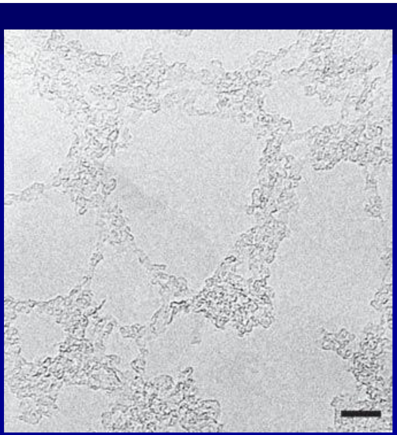
Graphene photodetectors for high-speed optical communications

T. Mueller et al Nature Photonics 2010



TEM Imaging and dynamics of light atoms and molecules on graphene

J. Meyer et al,Nature 2008 (Berkeley)

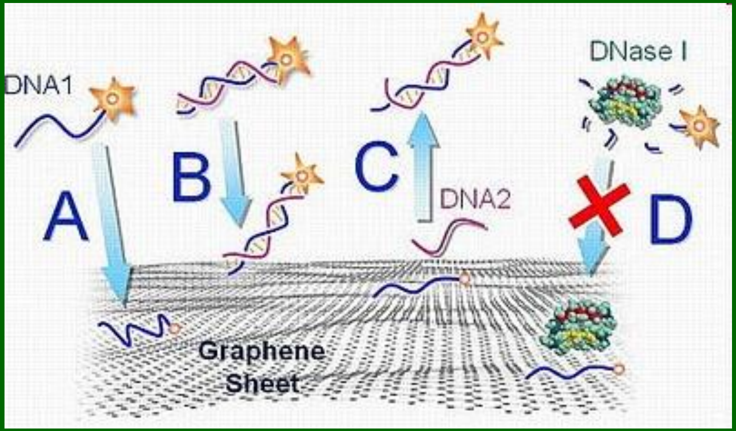


Bio -graphene

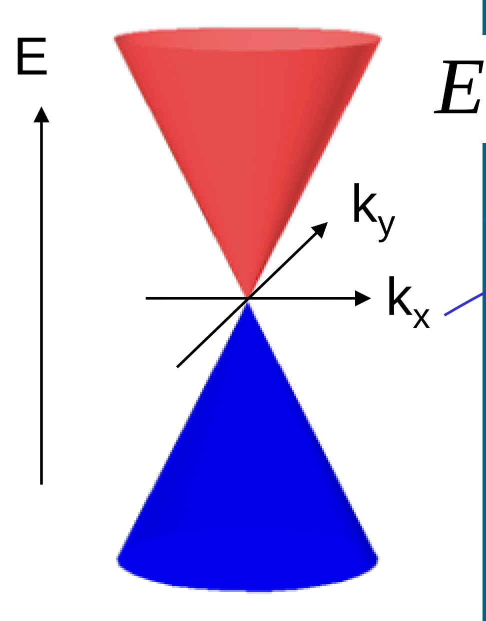
- DNA on graphene protected from break-down by enzymes.
- Differentiates between Single stranded and double stranded.
- Neuron growth enhancement

Potential for Drug delivery, gene therapy

Z. Tang, et al Small. (2010) PNNA)



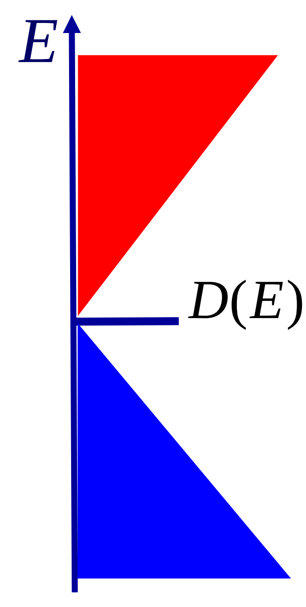
Electronic structure



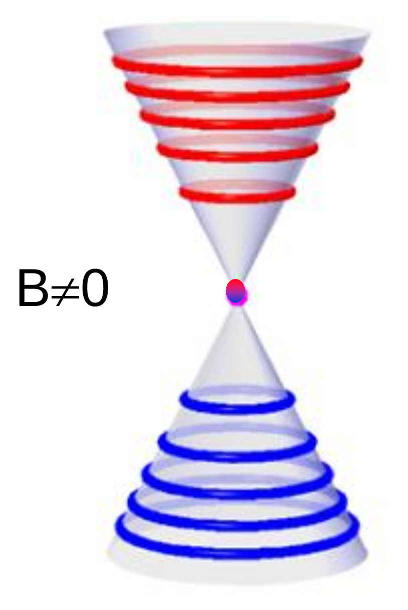
$$E(k) = v_F \hbar k$$

Dirac Point

Degeneracy = g_sxg_v =4



$$D(E) = \frac{2}{\pi\hbar^2}\frac{1}{v_F^2}|E|$$



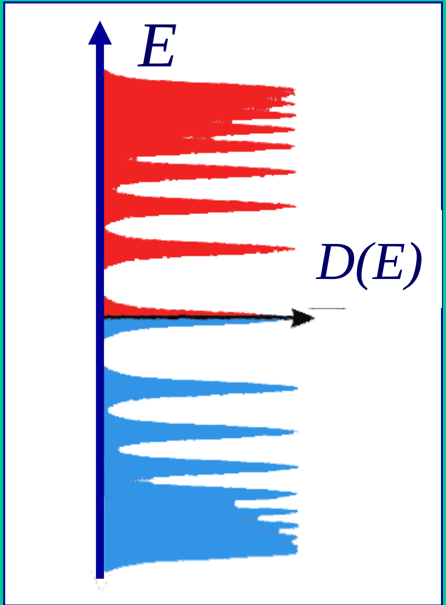
Landau Levels

McLure 1956

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

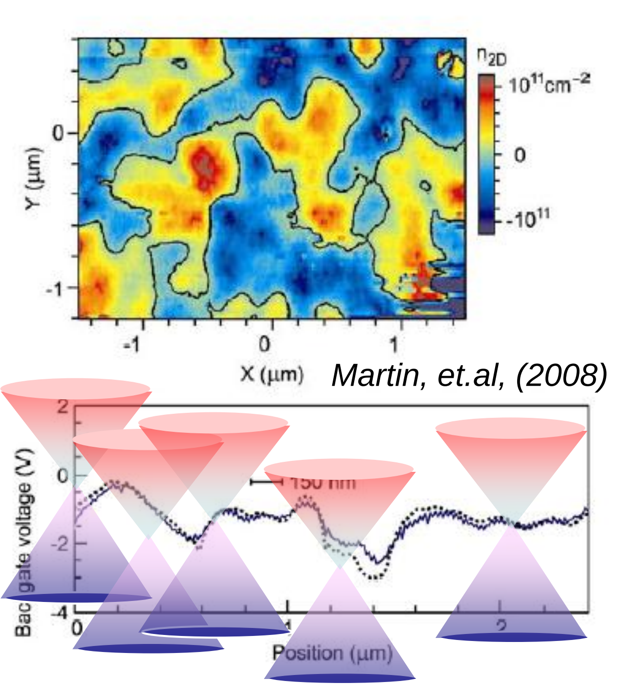
Flux Degeneracy = # of flux lines

$$n = \frac{B}{\phi_0}$$



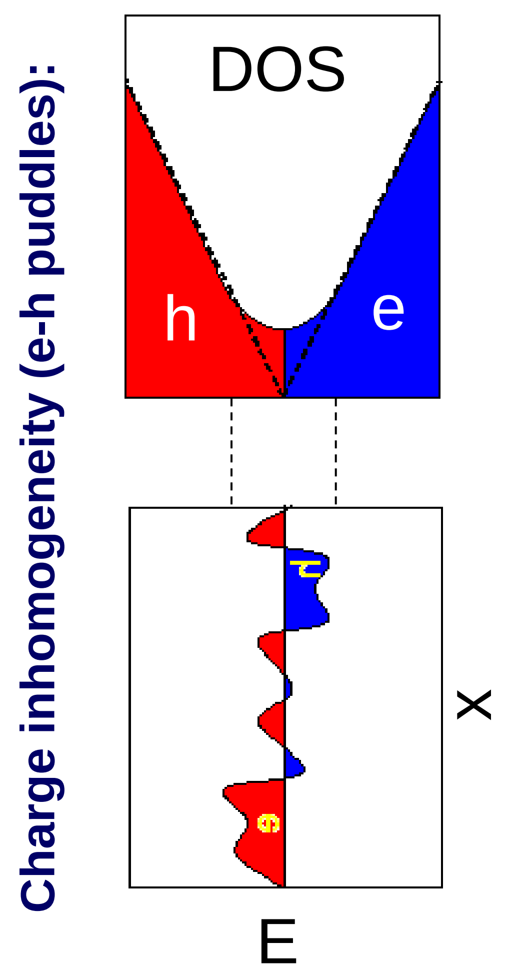
Graphene on SiO$_2$

SET microscopy

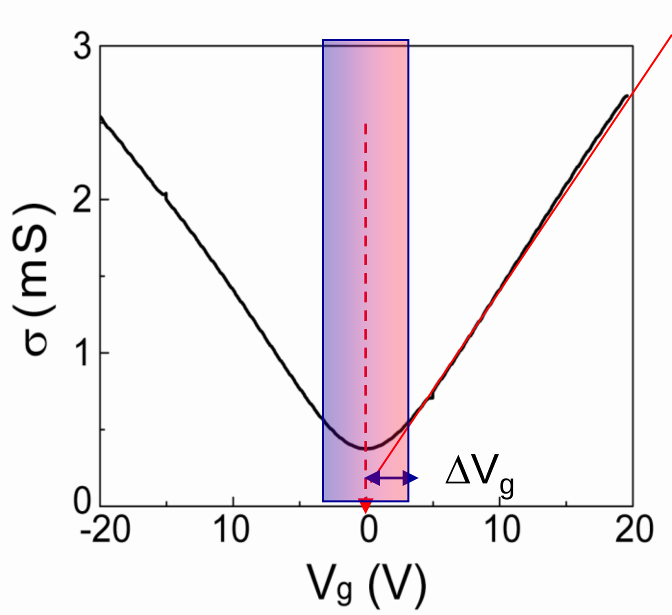


Martin, et.al, (2008)

Charge inhomogeneity (e-h puddles):



conductivity



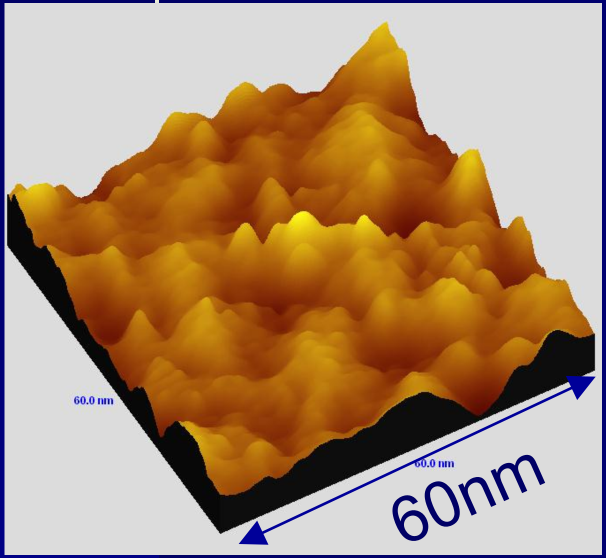
V_{gmin} ~1-10V
n_{min}~ 10^{11} cm $^{-2}$
(ΔE_F~30-100meV)

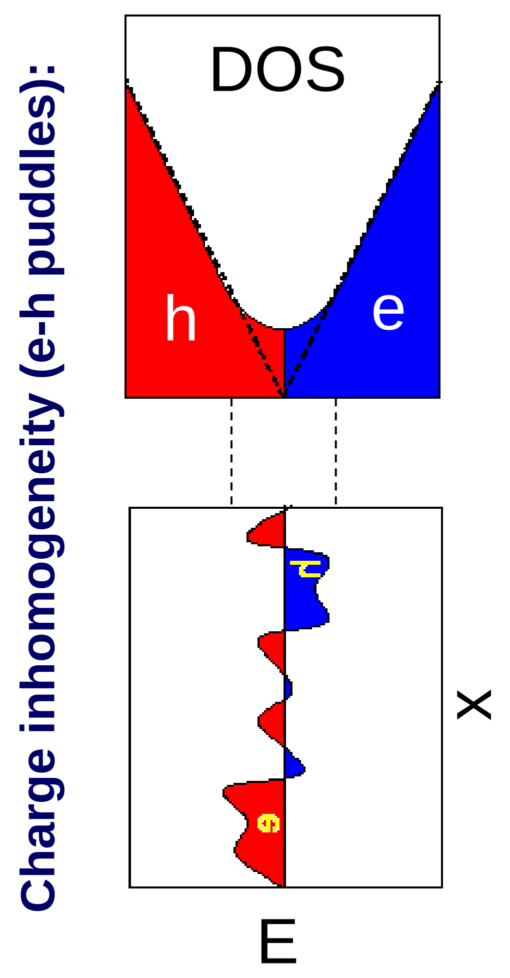
e-h puddles → smeared Dirac point

n_{min} minimum carrier density

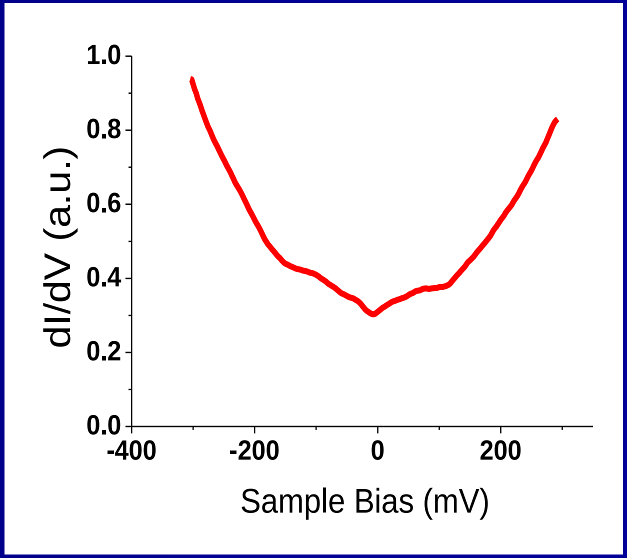
Graphene on SiO_2 : STM

STM topography

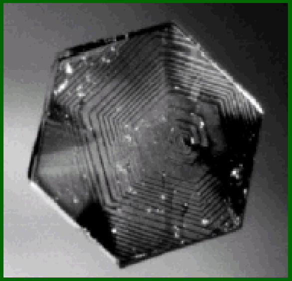




STM spectroscopy



Graphene on Graphite: STM



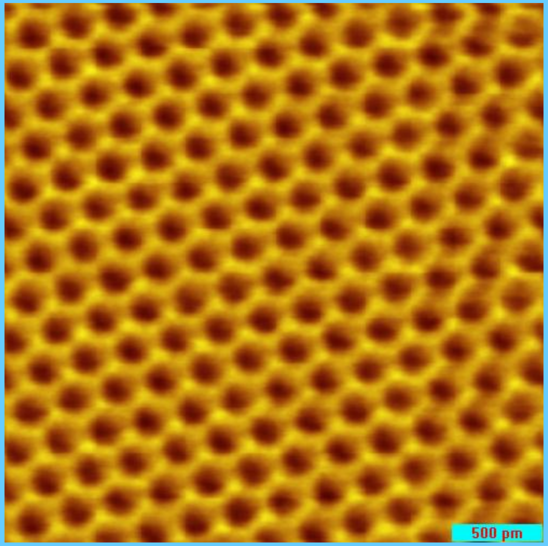
- Graphite
  - Clean
  - Lattice matched
  - Conductor

- STM – home built
  - Temperature T=4 (2K)
  - Magnetic field B=13 (15T)
  - Scan range 10^{-10} -10^{-3} m

- ➢Topography → structure
- ➢Spectroscopy → Density of states B=0
- ➢Spectroscopy → Density of states B>0

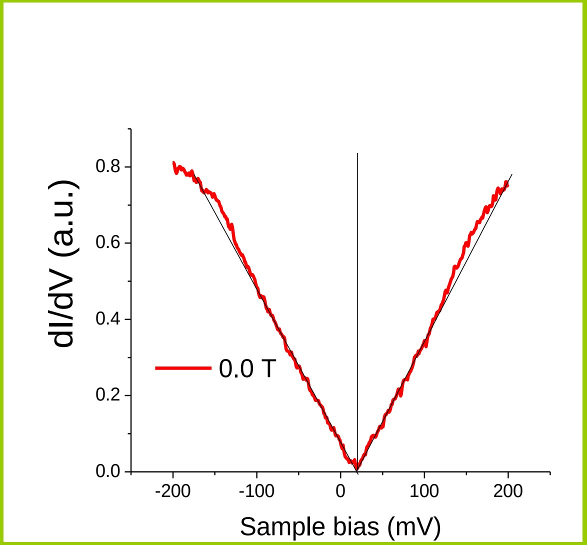
STM: Graphene on Graphite

topography



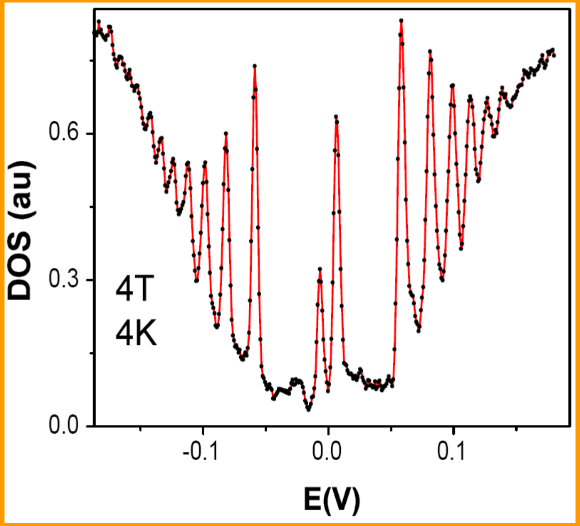
B=0 spectroscopy

Linear DOS



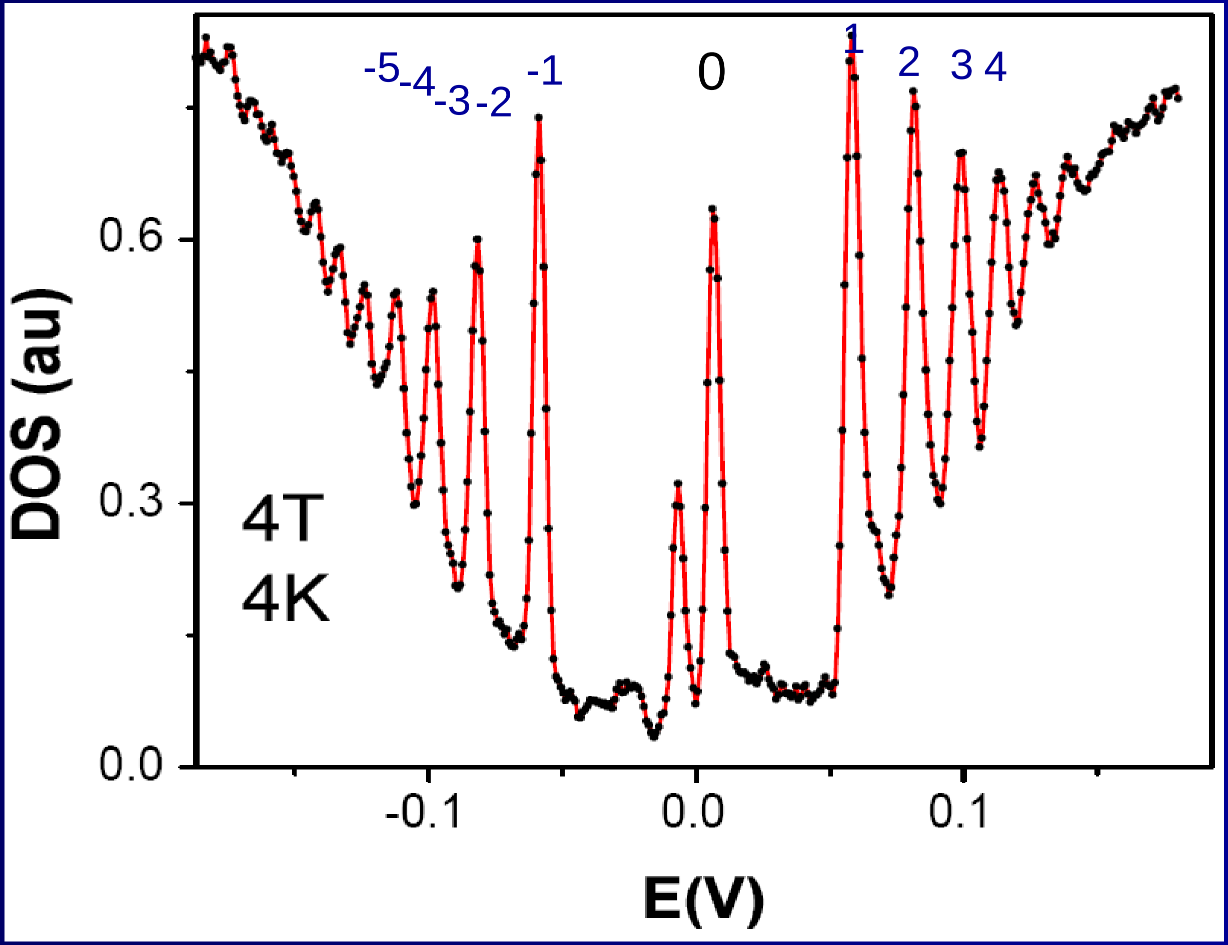
B>0 spectroscopy

Landau levels



Landau level spectroscopy

G. Li , E.Y. A - Nature Physics, 3, 623 (2007)
G. Li, A. Luican, E. Y. A., Phys. Rev. Lett (2009)



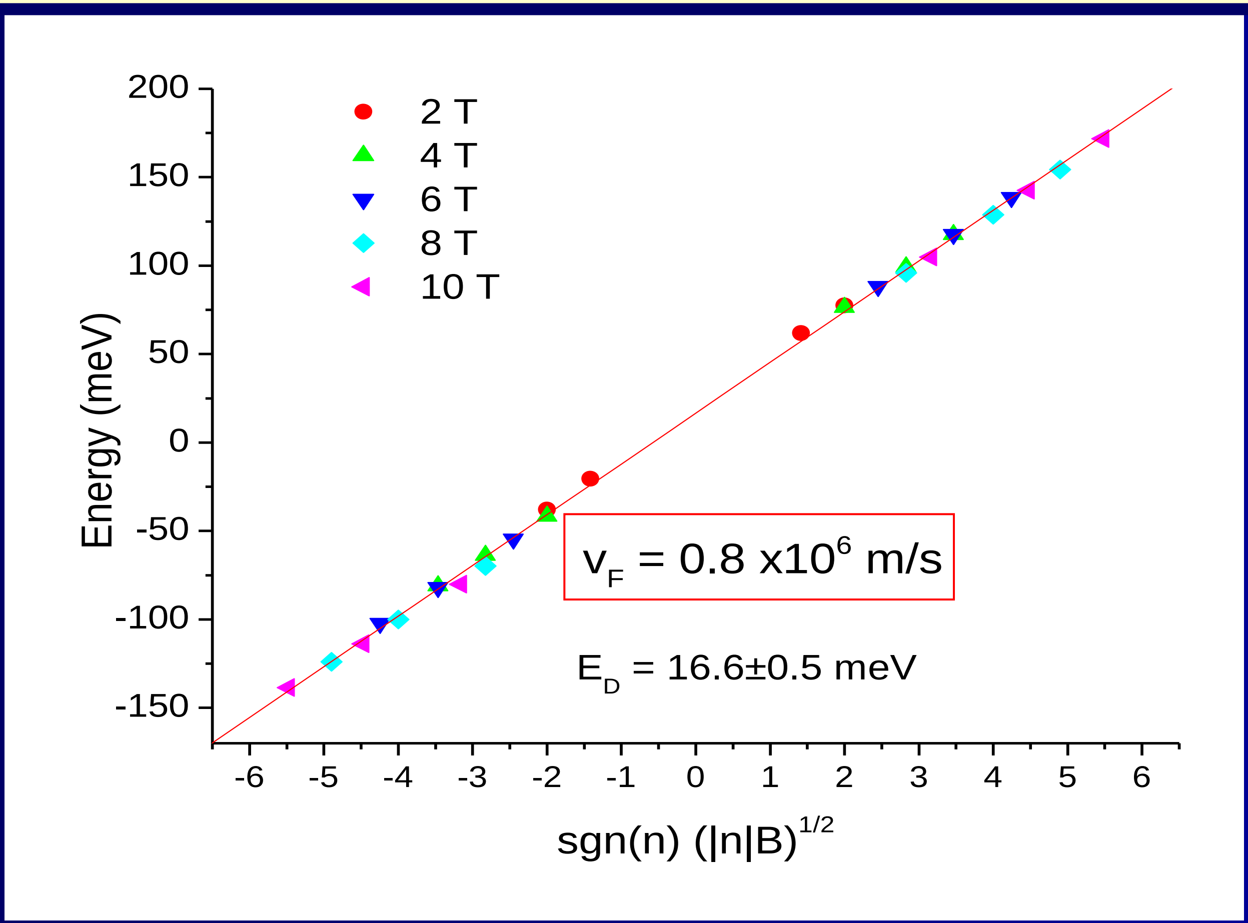
SiC: Miller et al Science 2009

Massless Dirac Fermions

G. Li , E.Y. A - Nature Physics, 3, 623 (2007)

G. Li, A. Luican, E. Y. A., Phys. Rev. Lett (2009)

$$E_j = \pm v_F \sqrt{2e\hbar B|N|}, \quad N = 0, \pm 1, \pm 2 \ldots$$

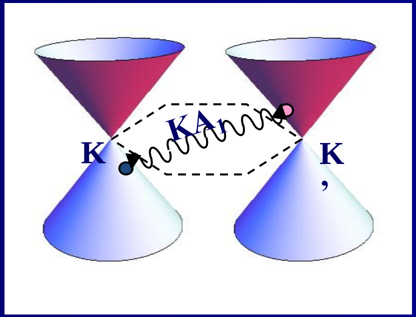


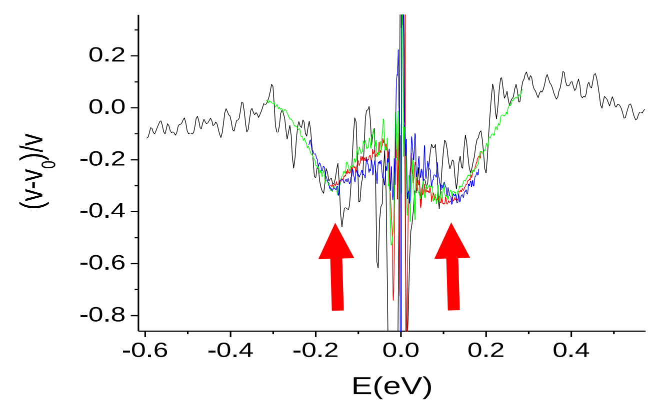
Graphene on graphite other results

G. Li , E.Y. A - Nature Physics, 3, 623 (2007)
G. Li, A. Luican, E. Y. A., Phys. Rev. Lett (2009)

- Electron-phonon interactions
  - Slow down of quasiparticles

$$v_F = 0.8 \times 10^6 m/s$$



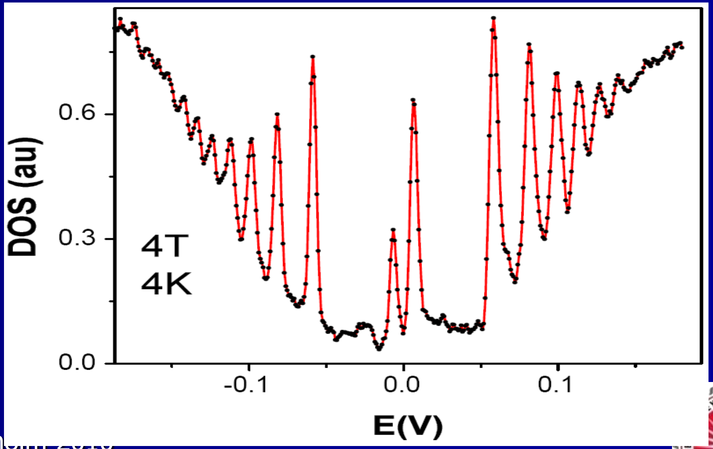


- e-e interactions
  - Quasiparticle lifetime

$$\tau_{qp} \propto E^{-1} \approx 9\, ps/meV$$

- Gap at Dirac point
  - broken symmetry gap

$$\Delta = m v_F^2 \sim 10 meV$$

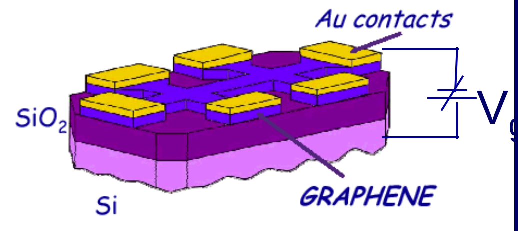


skip

Quantum Hall effect in graphene on SiO_2

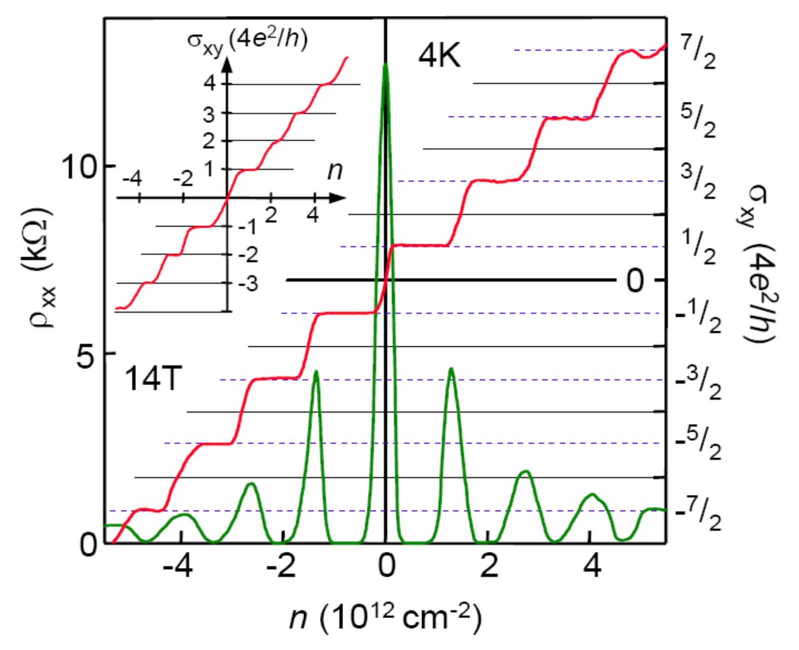
Two-dimensional gas of massless Dirac fermions in graphene

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]



K. Novoselov et al Nature 2005

Y. Zhang et al , Nature 2005



Nobel symposium Stockholm 2010

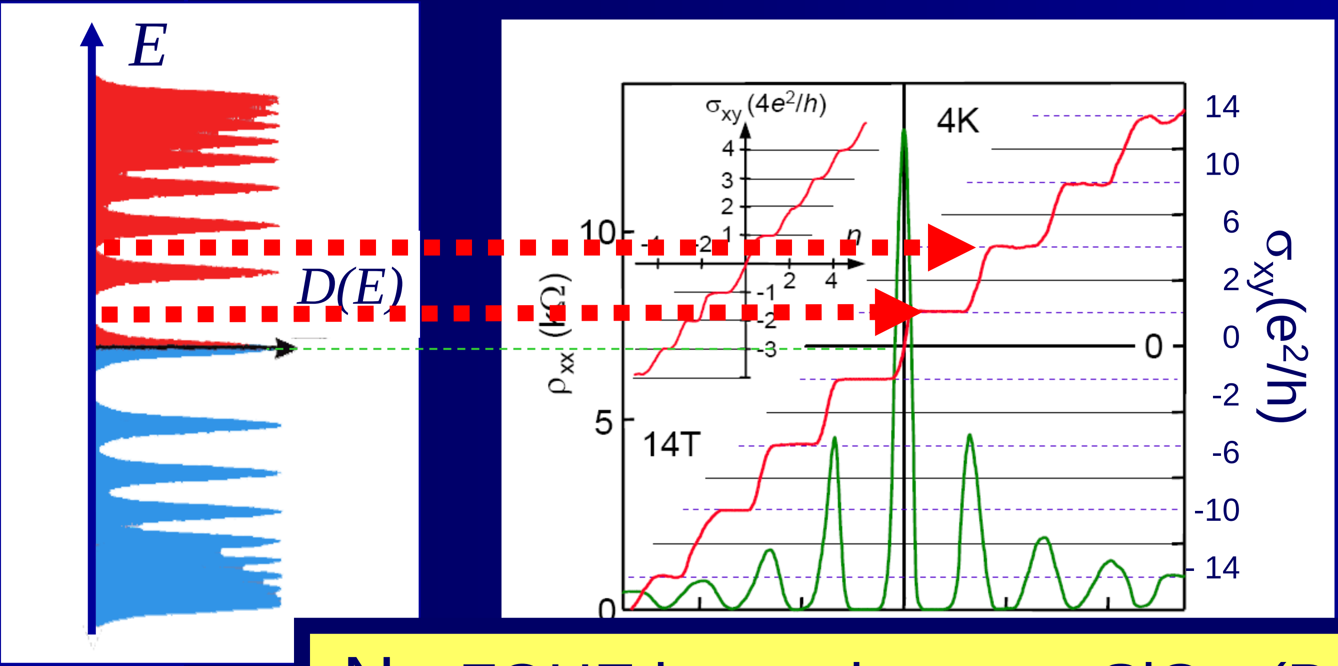
Quantum Hall Effect

Number of edge modes is topological “Chern number”

- Each filled Landau level contributes *g* edge modes (g degeneracy)
- Each edge mode contributes one quantum of Hall conductance

$$\sigma_{xy} = \nu \frac{e^2}{\hbar}$$

$$\nu = g(N + 1/2) = \pm 2, \pm 6$$
$$g = 4\ , N = 0, \pm 1, ..$$



Single particle physics

No FQHE in graphene on SiO_2 (B< 45T)

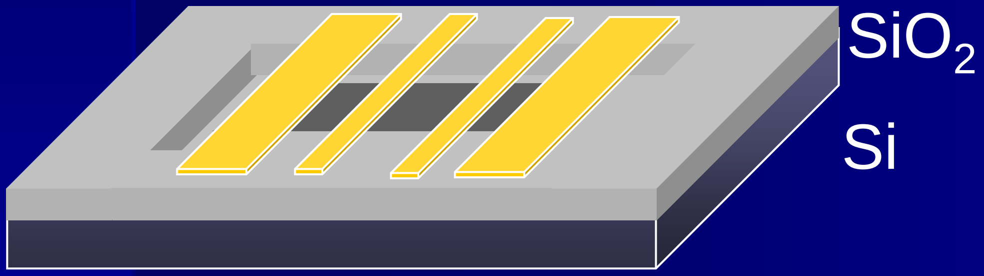
Correlation-challenge

Suspended Graphene

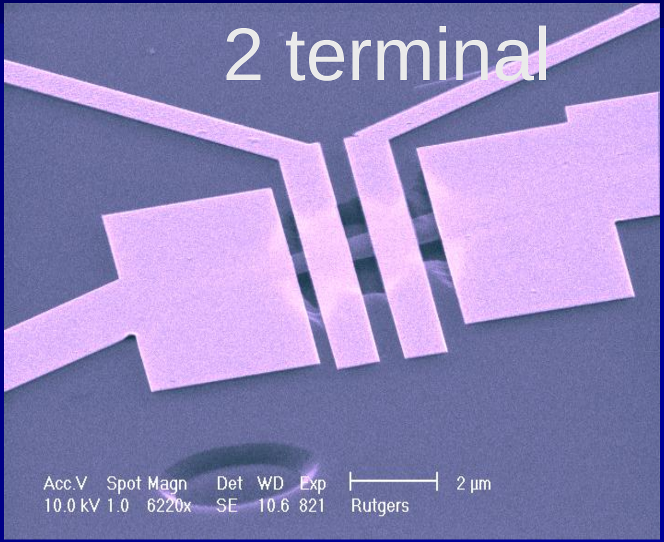
- X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)
- Bolotin et al , Solid State Communications (2008)

- Substrate roughness
- Trapped charges
- Quench condensed ripples

Get rid of the substrate!



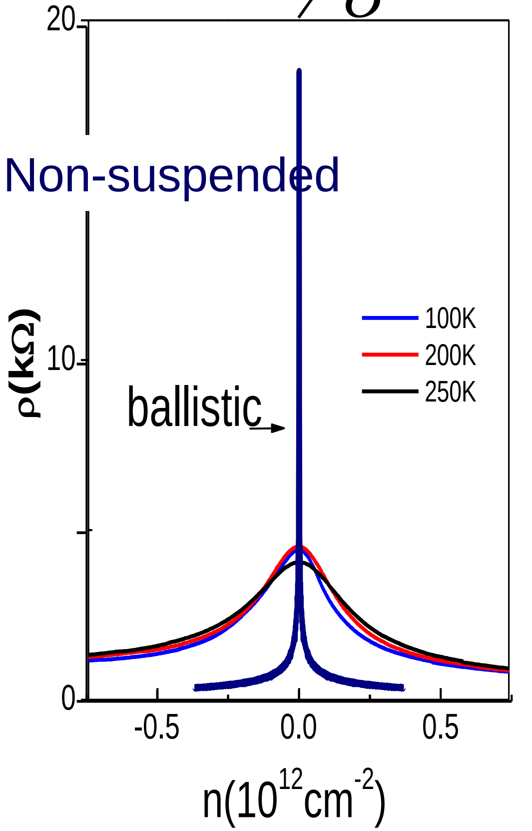
L< 1 μm

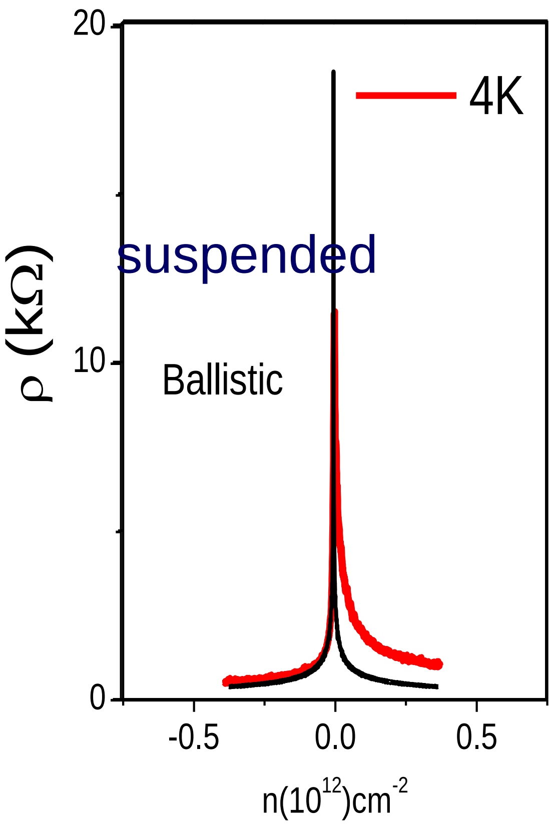


Non-Suspended versus Suspended Graphene

- X. Du, I. Skachko, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)

$$\rho = 1/\sigma$$





Non-Suspended versus Suspended Graphene

- X. Du, I. Skachako, A. Barker, E. Y. A. Nature Nanotech. 3, 491 (2008)

Non suspended

$\sigma \sim n$, $l_{mfp} << L_{sample}$

$n_{min} \sim 10^{11}$ cm^{-2}

$\mu \sim 10^4$ cm^2/ V s

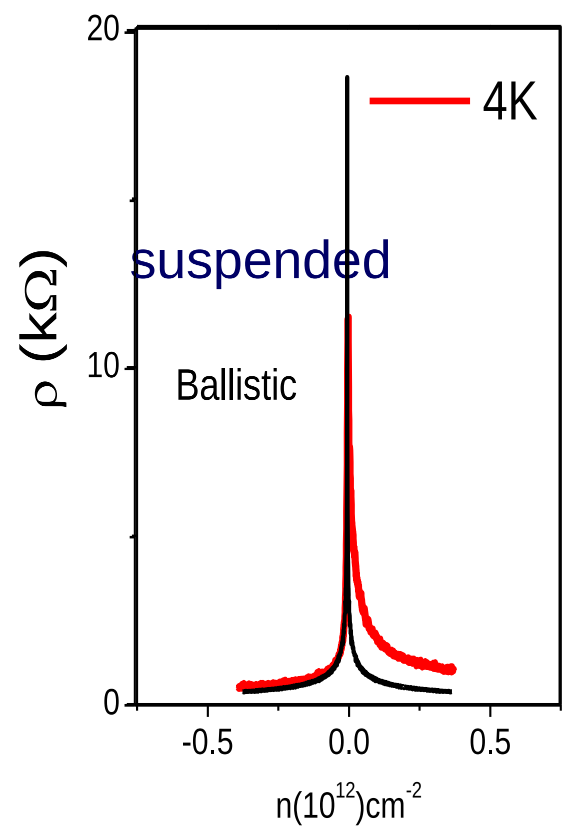
Suspended

$\sigma \sim n^{1/2}$, $l_{mfp} \sim L_{sample}$

$n_{min} \sim 10^9 – 10^{10}$ cm^{-2}

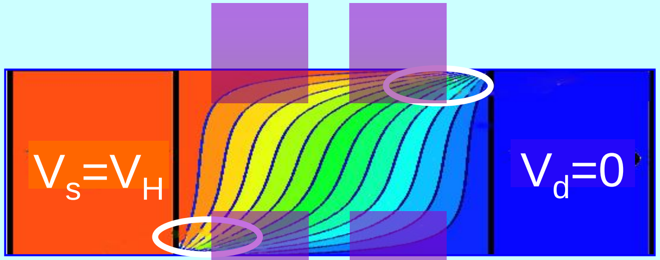
$\mu \sim 10^5 - 10^6$ cm^2/ V s

- Ballistic transport
- Approaching Dirac point



Suspended Graphene and QHE

Bolotin et al , Solid State Communications (2008)



Hall angle = 90º

The Hall-bar Standard

- No contact resistance
- Separates σ_{xy} and ρ_{xx}
- Activation gaps

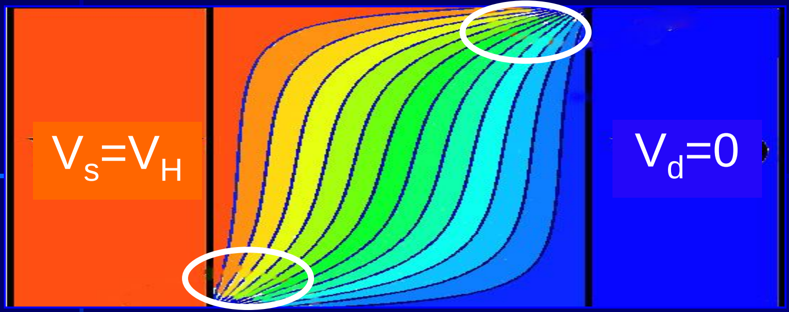
works for large samples

… NOT for small samples

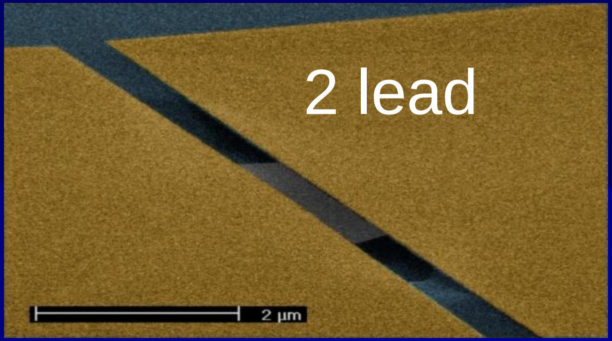
Suspended Graphene:

☞ No QHE in Hall bar configuration

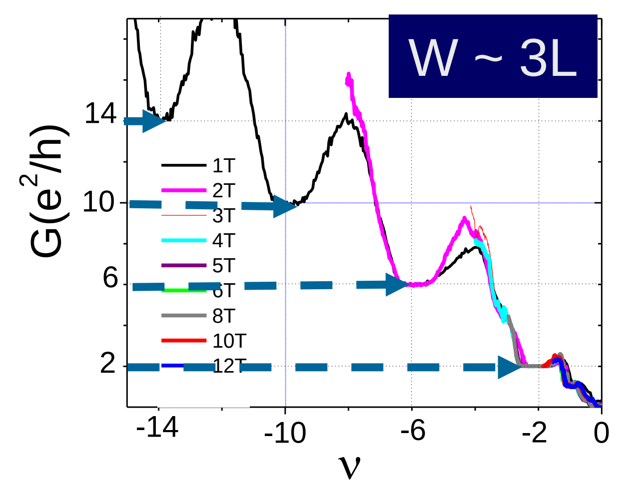
QHE in 2-terminal measurement



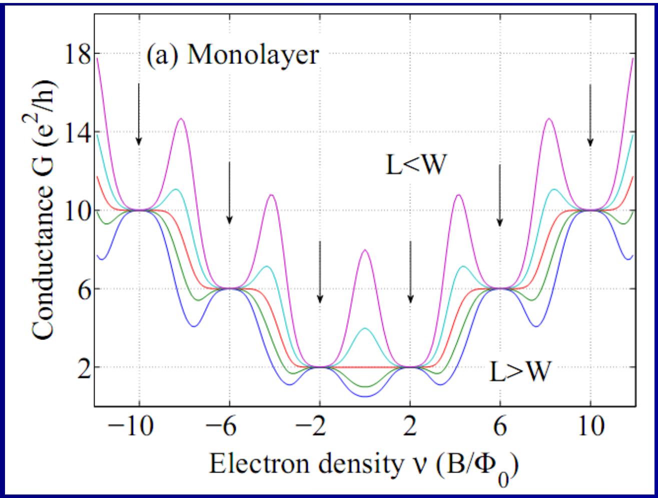
Hall angle = 90º



X. Du et al. Nature Nanotechnology (08)

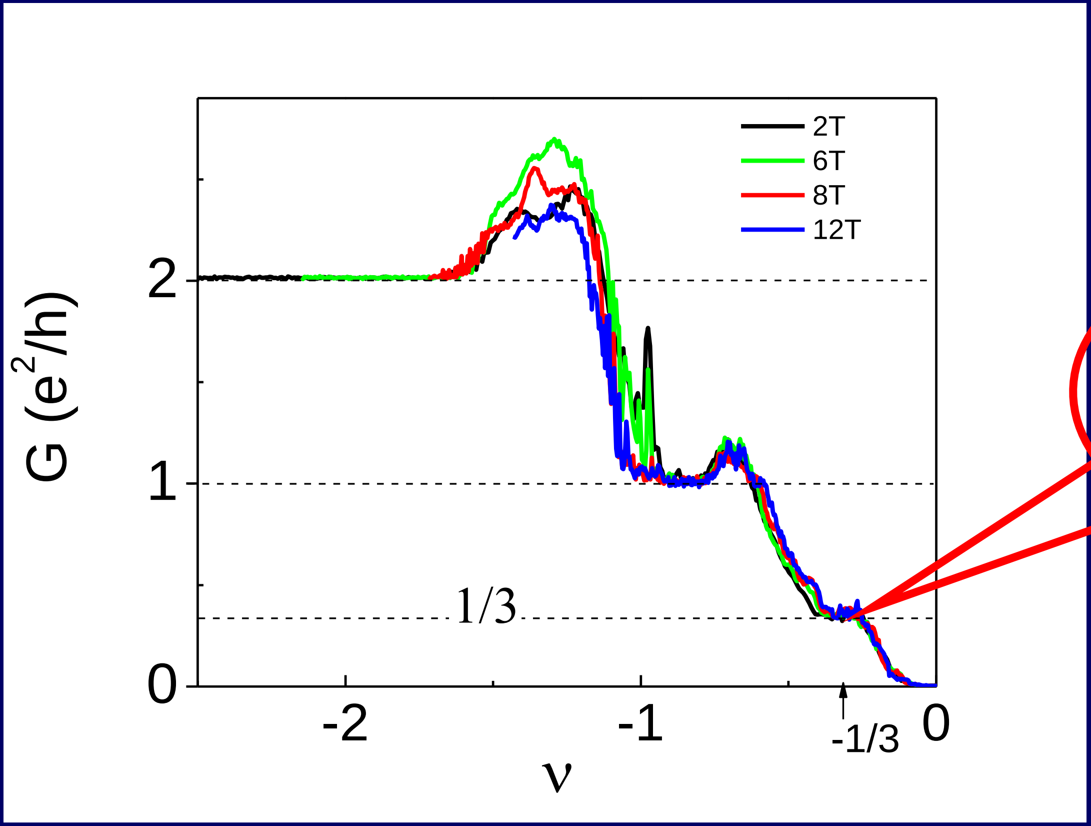


D. Abanin, L. Levitov, PRB (08)



FQHE in 2-terminal measurement

X. Du, I. Skachko, F. Duerr, A. Luican, EYA, Nature **462**, 192 (2009)



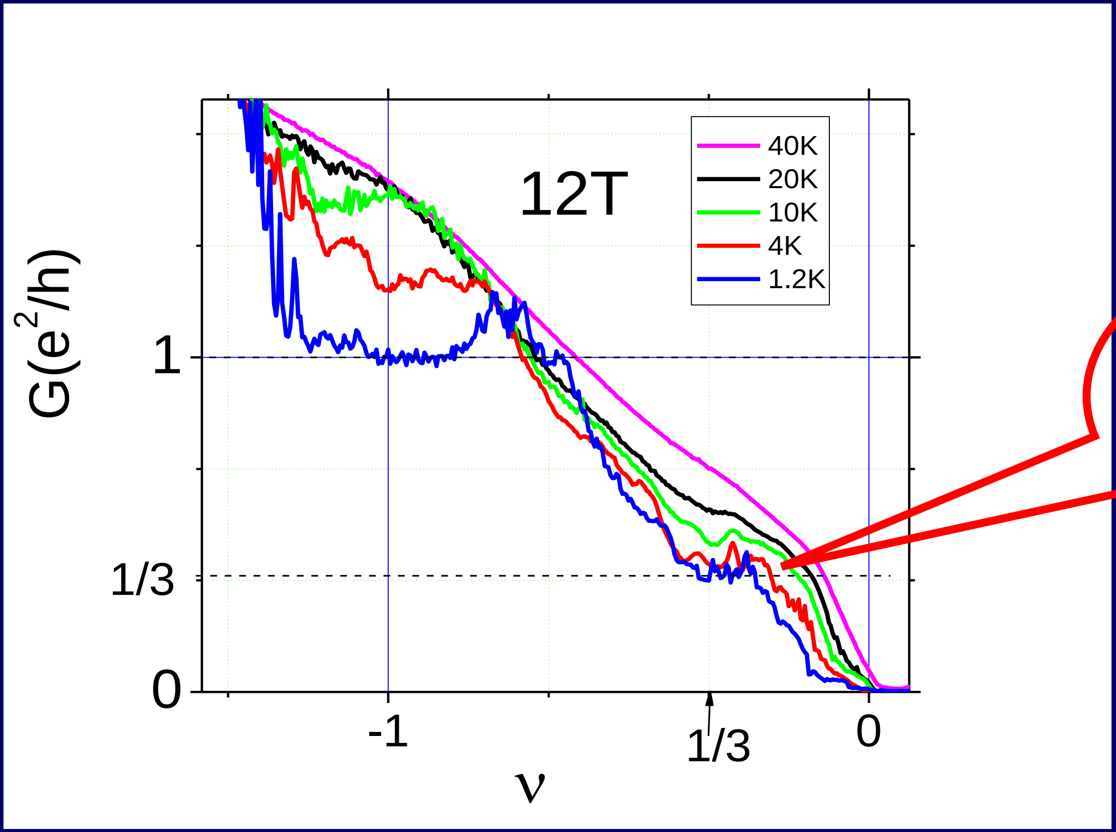
ν=1/3
FQHE

FQHE in graphene
Seen already at 2T

- Bolotin et al (Columbia) Nature 462 (2009)
- Geim & Novoselov (Manchester)

Suspended Graphene: two terminal measurement

X. Du, I. Skachko, F. Duerr, A. Luican, EYA, Nature **462**, 192 (2009)



ν=1/3
FQHE

FQHE in graphene

Seen already at 2T

Persists up to 20K (in 12T)

$\Delta_{1/3}$(12T)~ 4.4K

Δ_1(12T)~ 10K

D. Abanin, et al, PRB (2010)

Ground state of neutral graphene in field

Alicea & Fisher (2006)
Normura & Macdonald, (2006)
Abanin, Lee, & Levitov, (2007);

$\nu = 1$ valley split

ν=1 valley split
Zhang et al (07)

tilted field expt

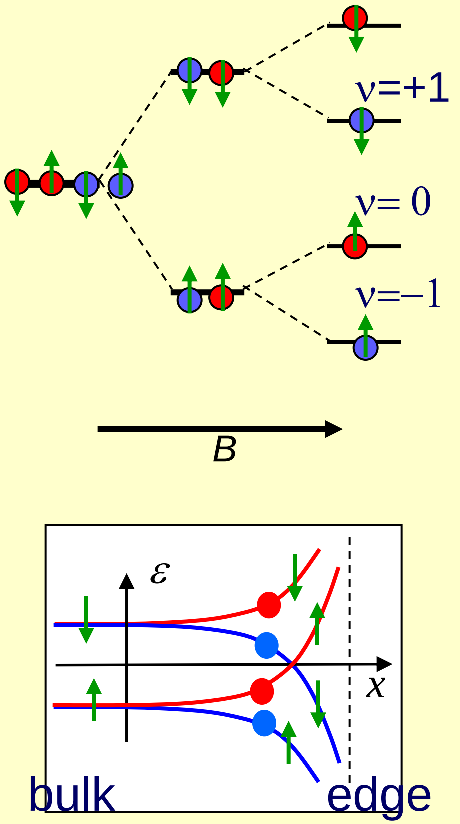
ν=0 conducting

Abanin et al (07)

Conductor

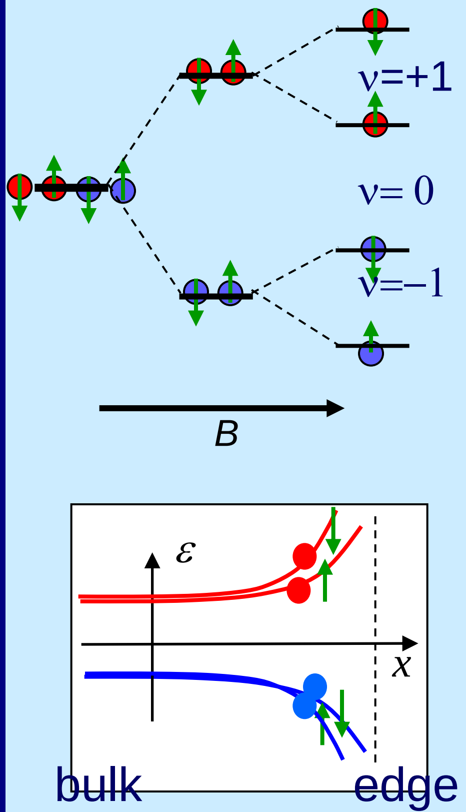
Spin first

$\Delta_{\text{Spin}} > \Delta_{\text{valley}}$



Valley first

$\Delta_{\text{Spin}} < \Delta_{\text{valley}}$



Alicea & Fisher (2006)
Gusynin & Sharpov (2006)

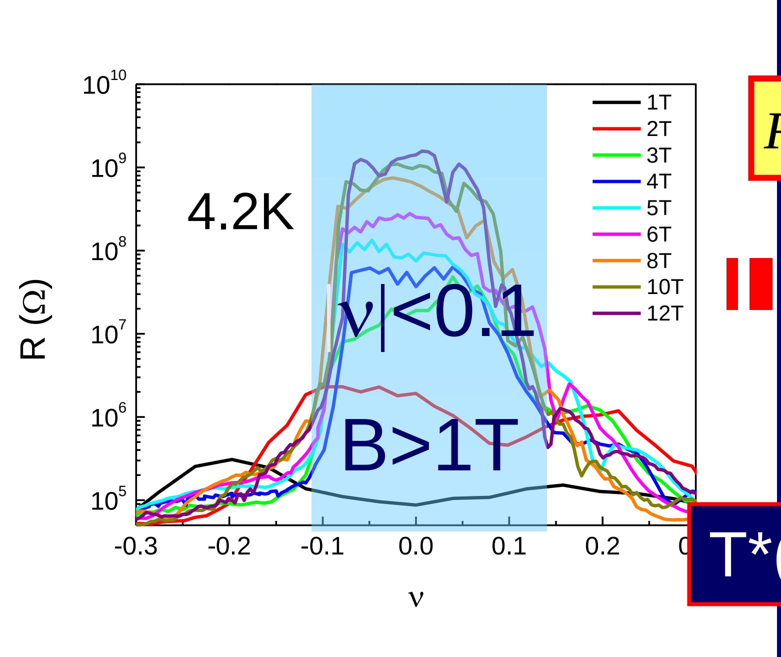
$\nu = 1$ spin split

ν=0 insulating
Checkelsky,
et al (08)

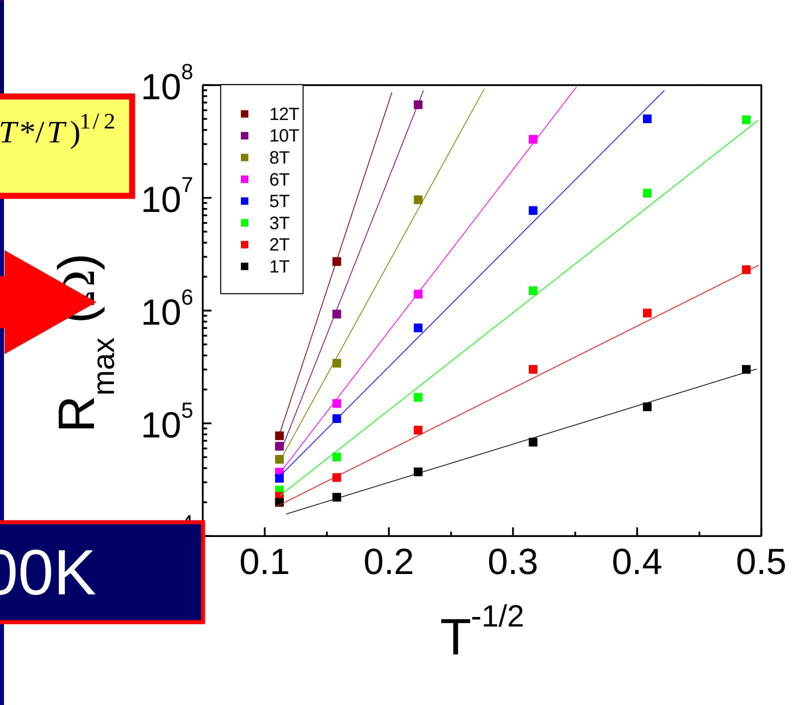
Insulator

Magnetically induced insulating phase

X. Du, I. Skachko, F. Duerr, A. Luican, EYA, Nature **462**, 192 (2009)



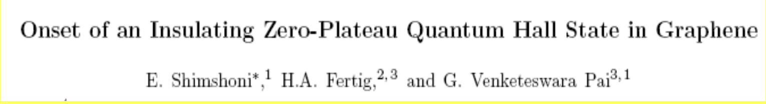
$$R_{max} \sim R_0 e^{(T^*/T)^{1/2}}$$



T*(4T)~ 100K

Insulating phase → Correlated electron state:

Spin polarized bulk + “broken edges”

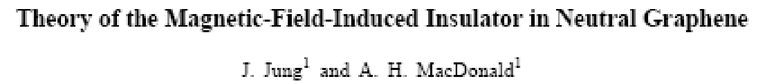


Onset of an Insulating Zero-Plateau Quantum Hall State in Graphene

E. Shimshoni*,[1] H.A. Fertig,[2,3] and G. Venketeswara Pai[3,1]

bulk antiferromagnet+no edge states

- CDW or SDW

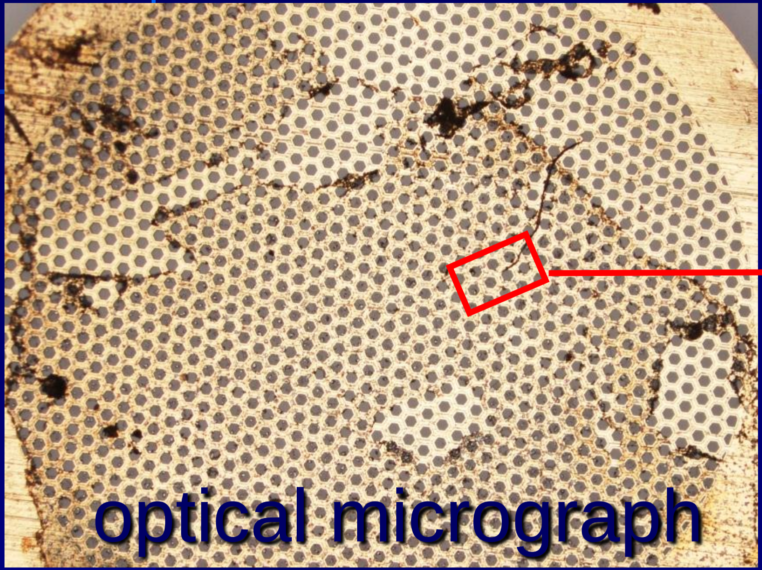


Theory of the Magnetic-Field-Induced Insulator in Neutral Graphene

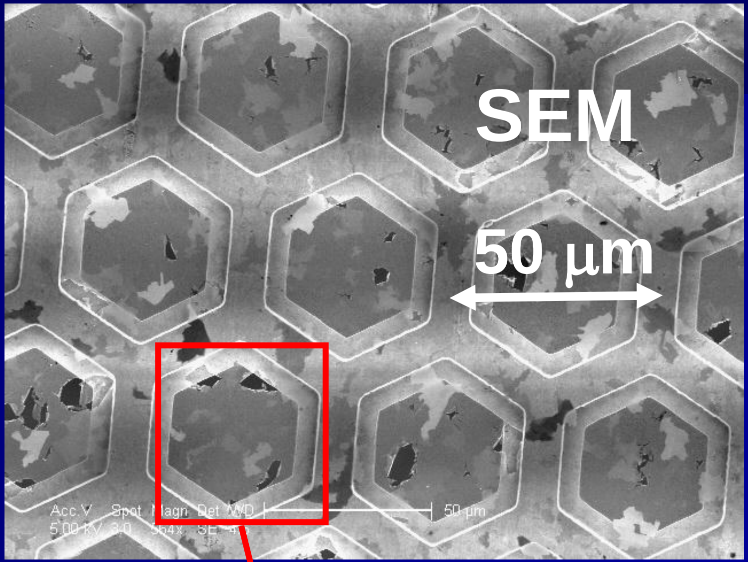
J. Jung[1] and A. H. MacDonald[1]

Supended CVD Graphene membrane

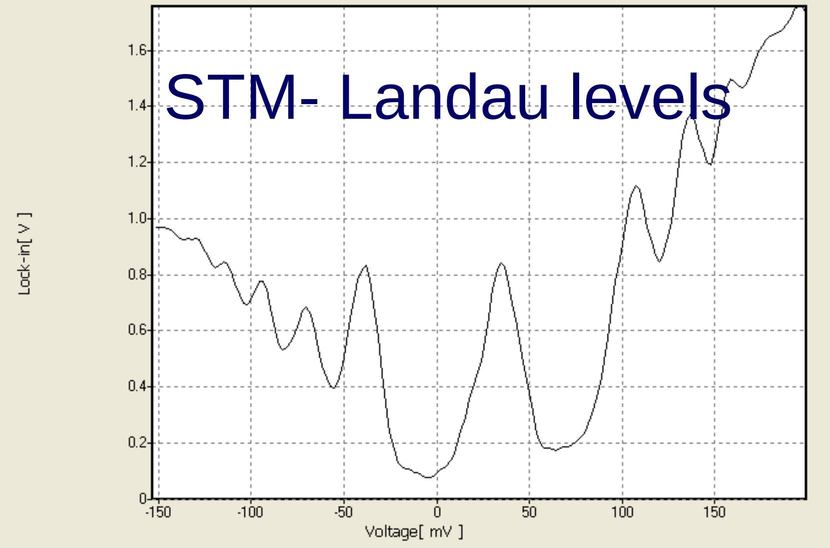
with: A. *Reina, J. Kong* (MIT) R. R. *Nair, K. Novoselov, A. Geim (Manchester)*



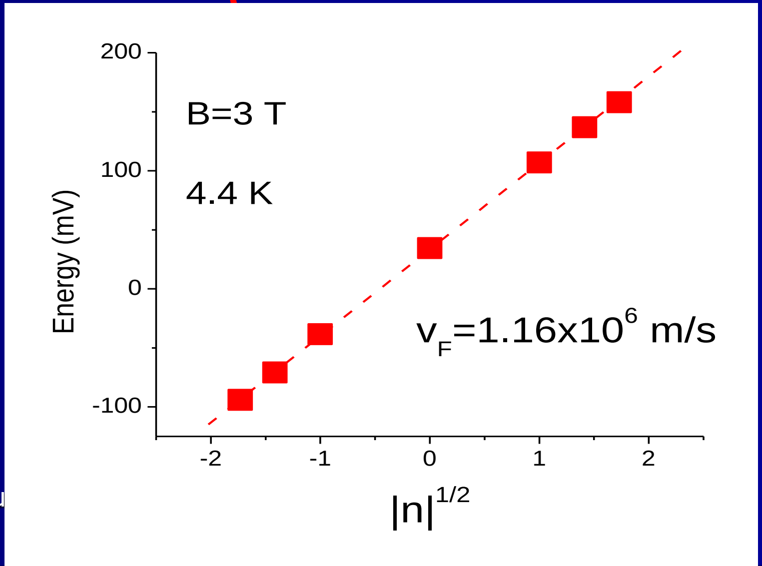
optical micrograph



SEM



STM- Landau levels



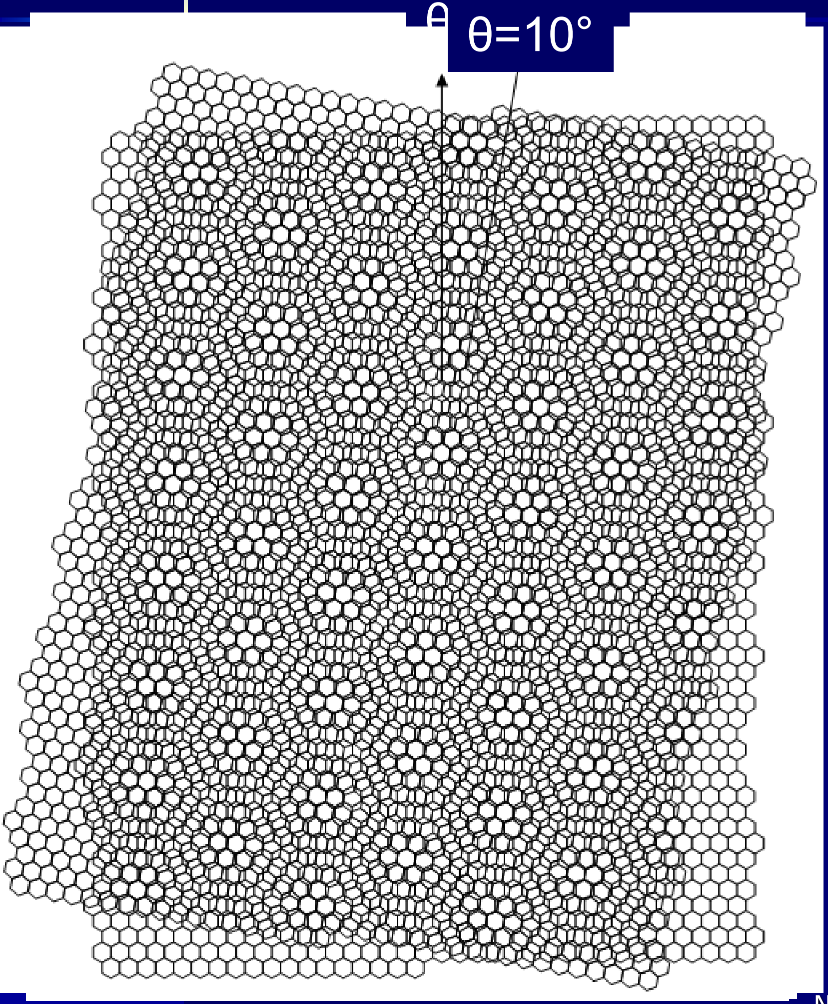
B=3 T

4.4 K

v_F=1.16x10^6 m/s

Twisted graphene

Twist between top layers → Moiré pattern



$$\cos(\theta_i) = \frac{3i^2+3i+1/2}{3i^2+3i+1}, i = 0, 1, 2, 3...$$

- Period of superstructure :

$$L = a_0\sqrt{3i^2 + 3i + 1}$$

$a_0 \approx 2.46$ Å

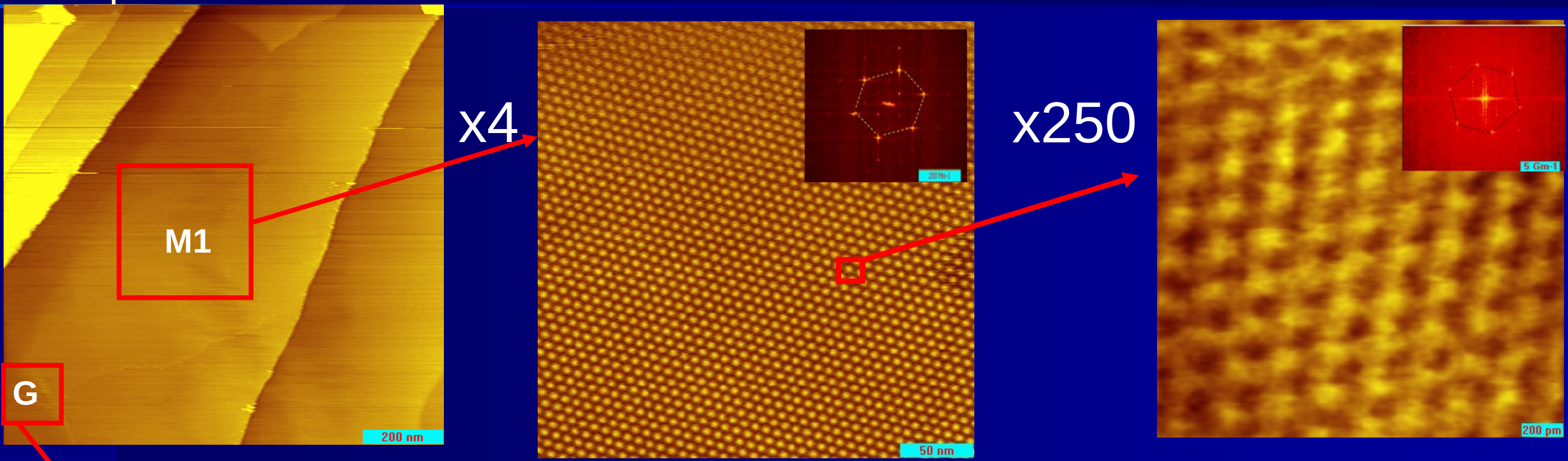
Lopes dos Santos et al PRL 99, 256802 (2007).

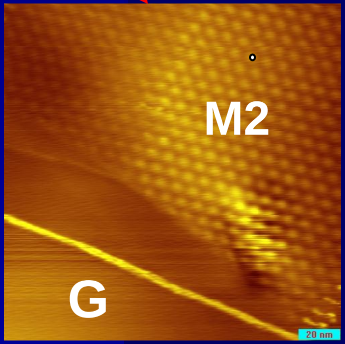
STM topography: Moiré superstructure

G. Li, et al Nature Physics (2010)

superstructure L=7.5nm

$\theta=1.79^{o}$

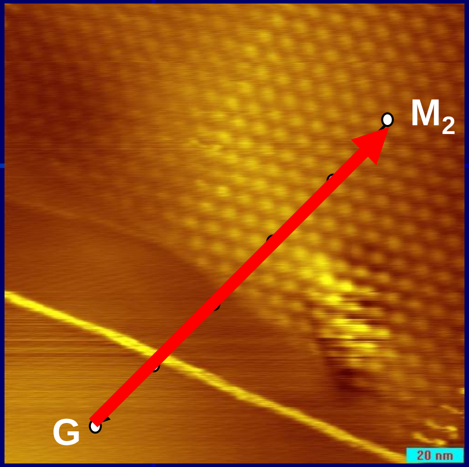


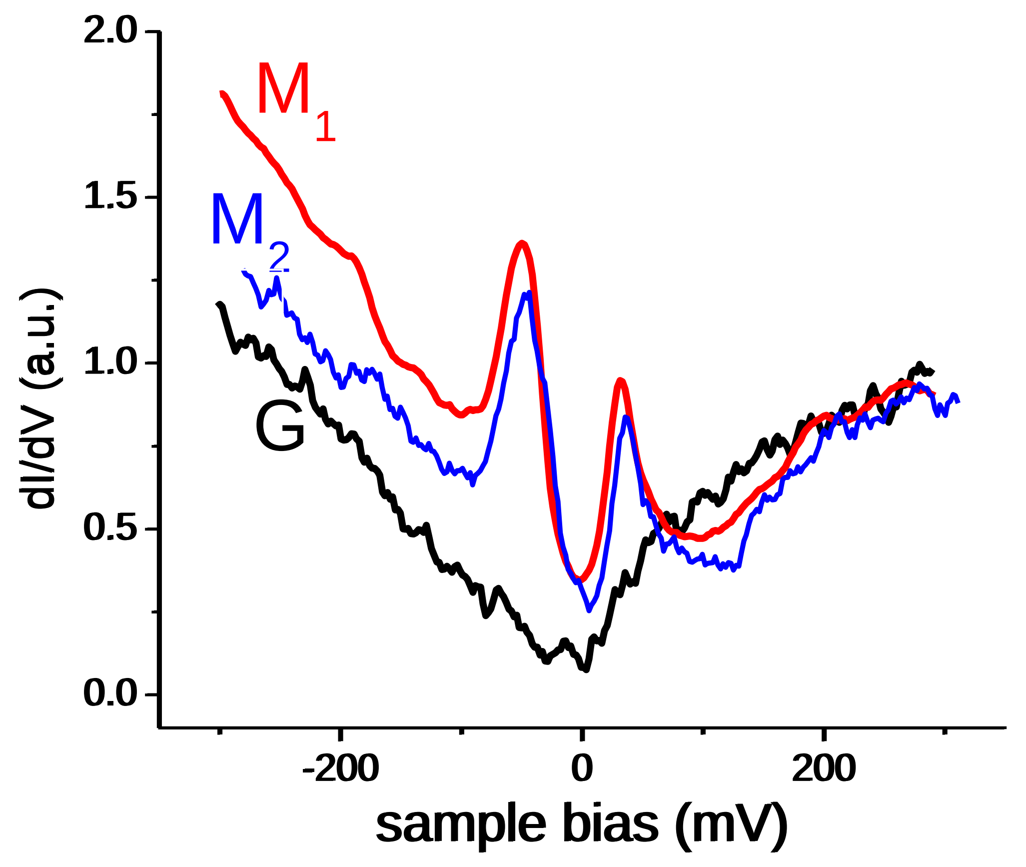


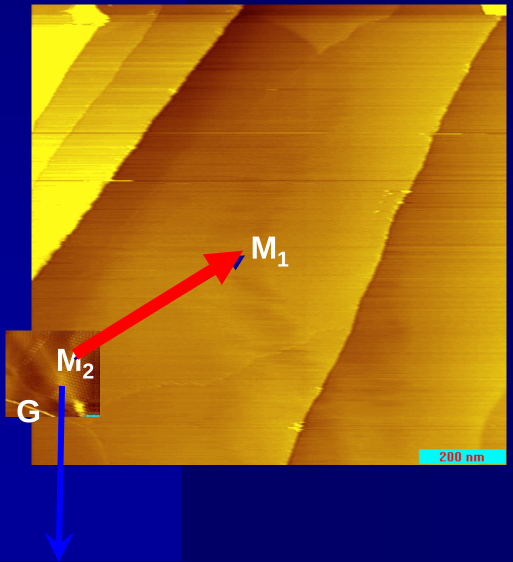
Boundary of area with superstructure

Spectroscopy – Van Hove singularities

G. Li, et al Nature Physics (2010)

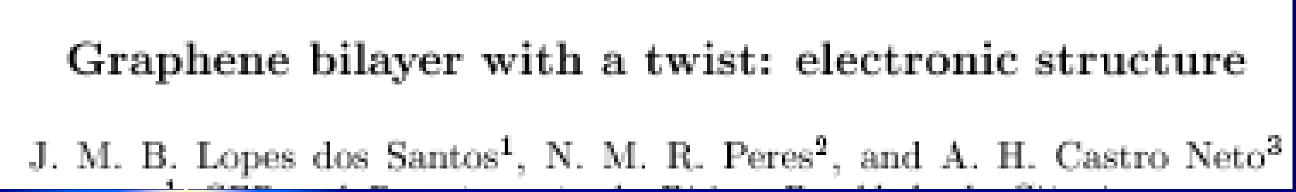






Two peak structure only in twisted region

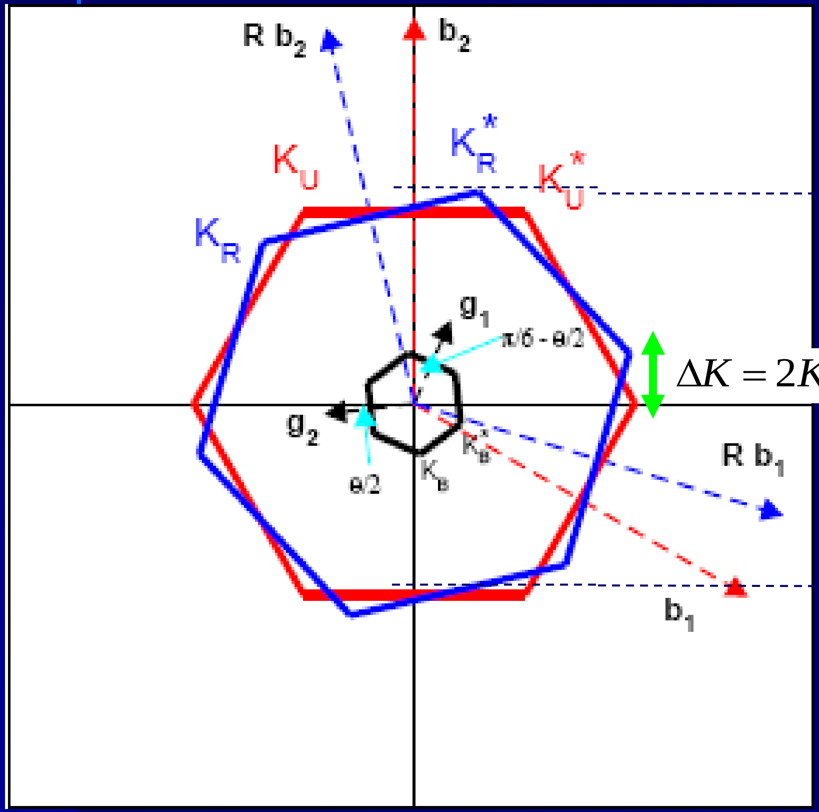
Electronic dispersion of twisted layers



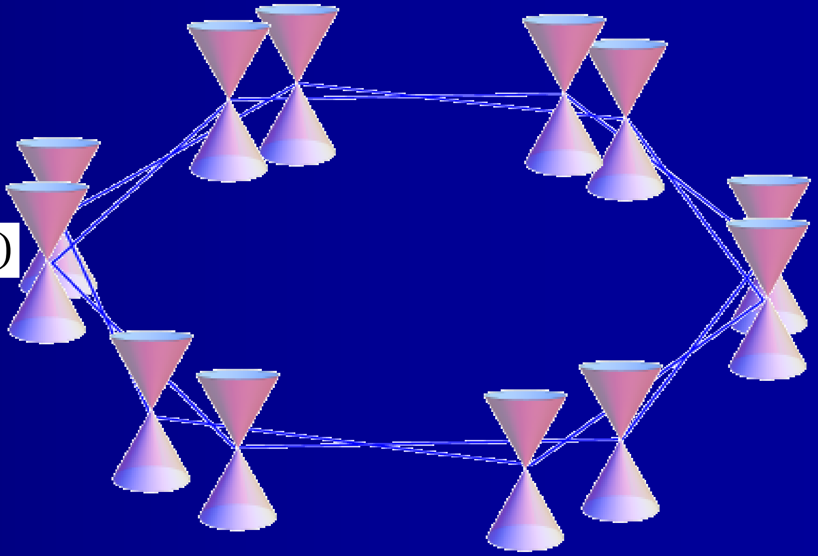
Graphene bilayer with a twist: electronic structure

J. M. B. Lopes dos Santos[1], N. M. R. Peres[2], and A. H. Castro Neto[3]

PRL 99, 256802 (2007).



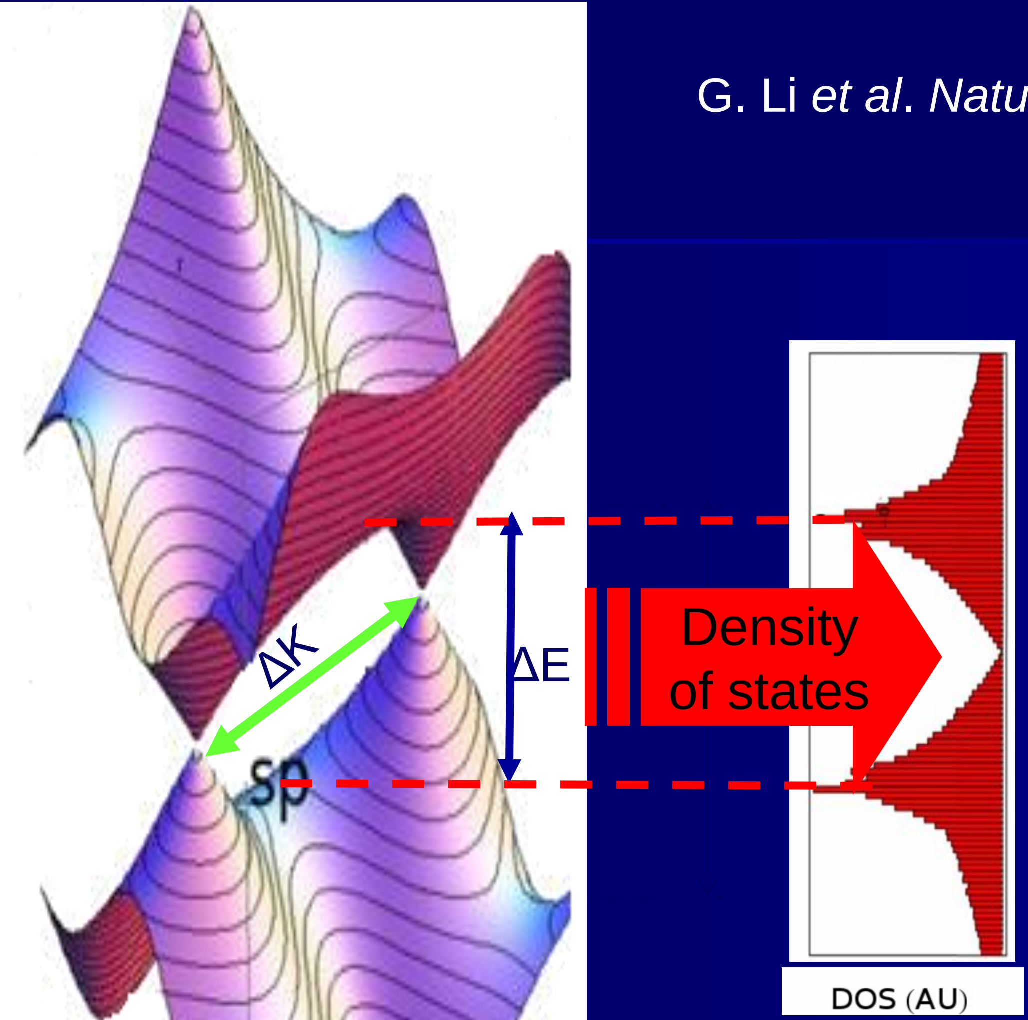
$$\Delta K = 2K\sin(\theta/2)$$

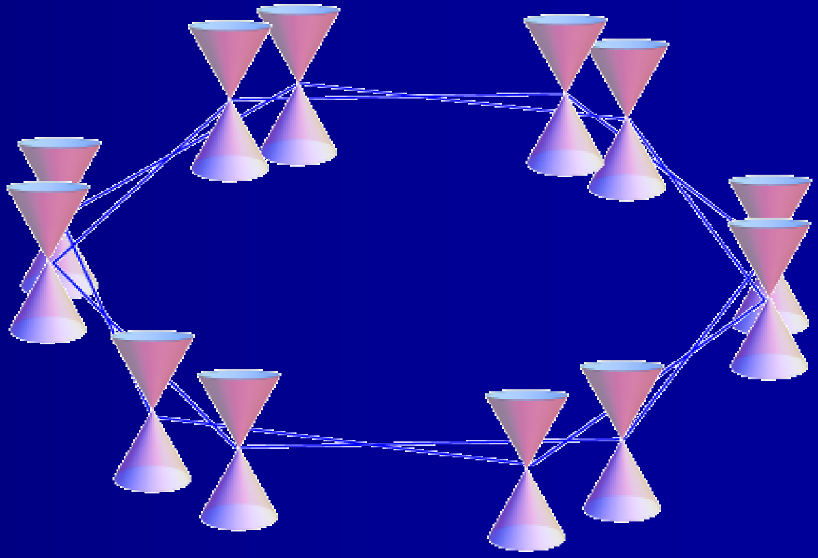


S. Shallcross, et al 2009
G. Mele PRB 2010
Bistrizer, MacDonald 2010

Van Hove singularities

G. Li *et al*. *Nature Physics 6*, p109 (**2010)**

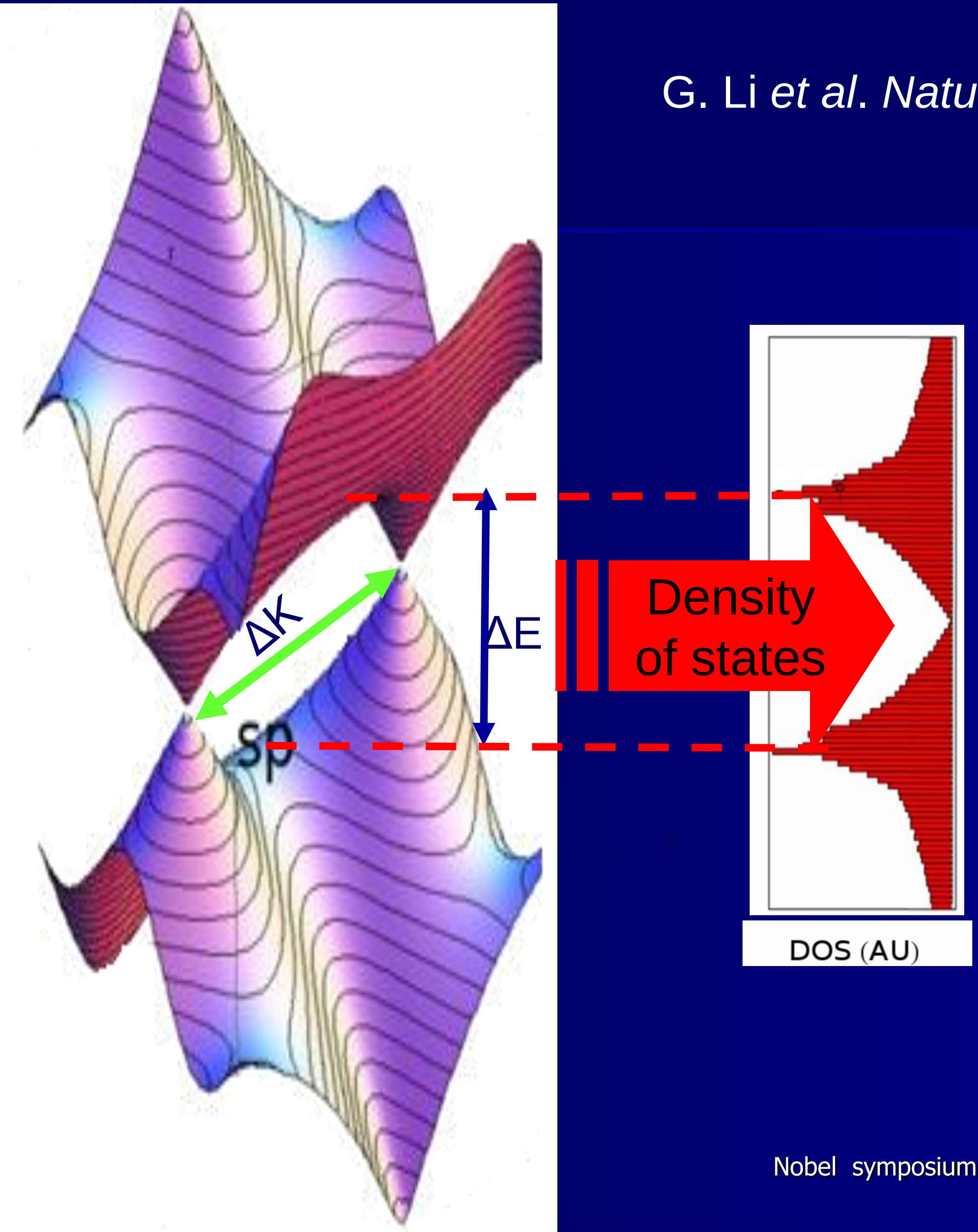


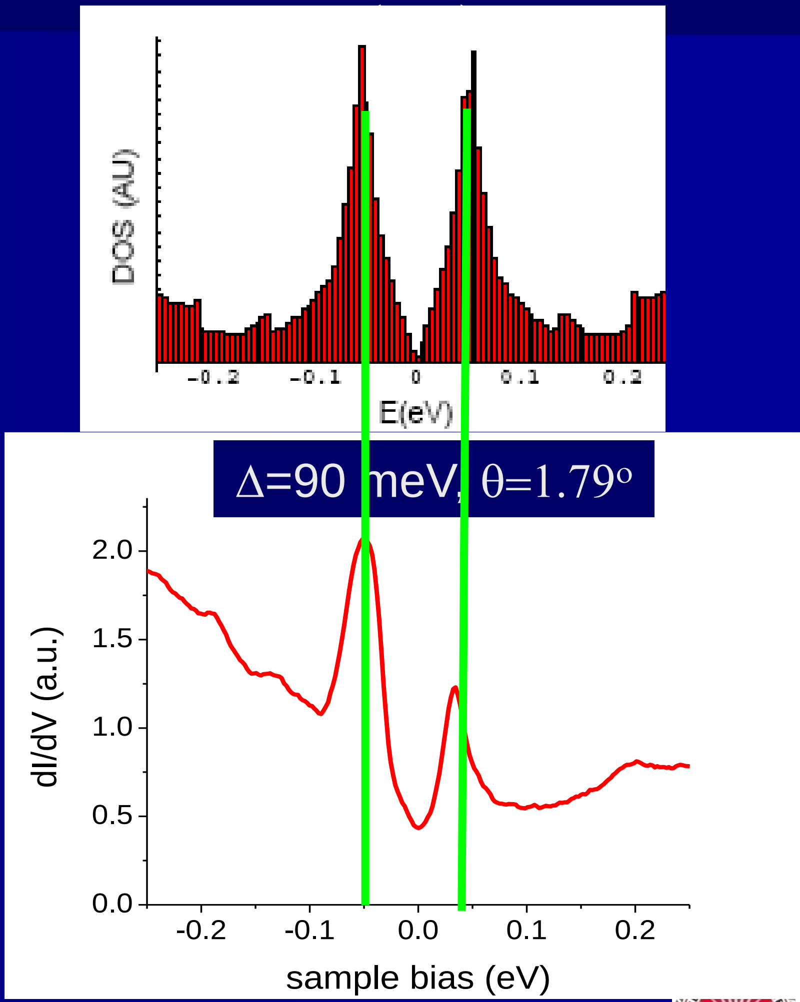


Twisted graphene develops strong *Van Hove singularities*

Van Hove singularities

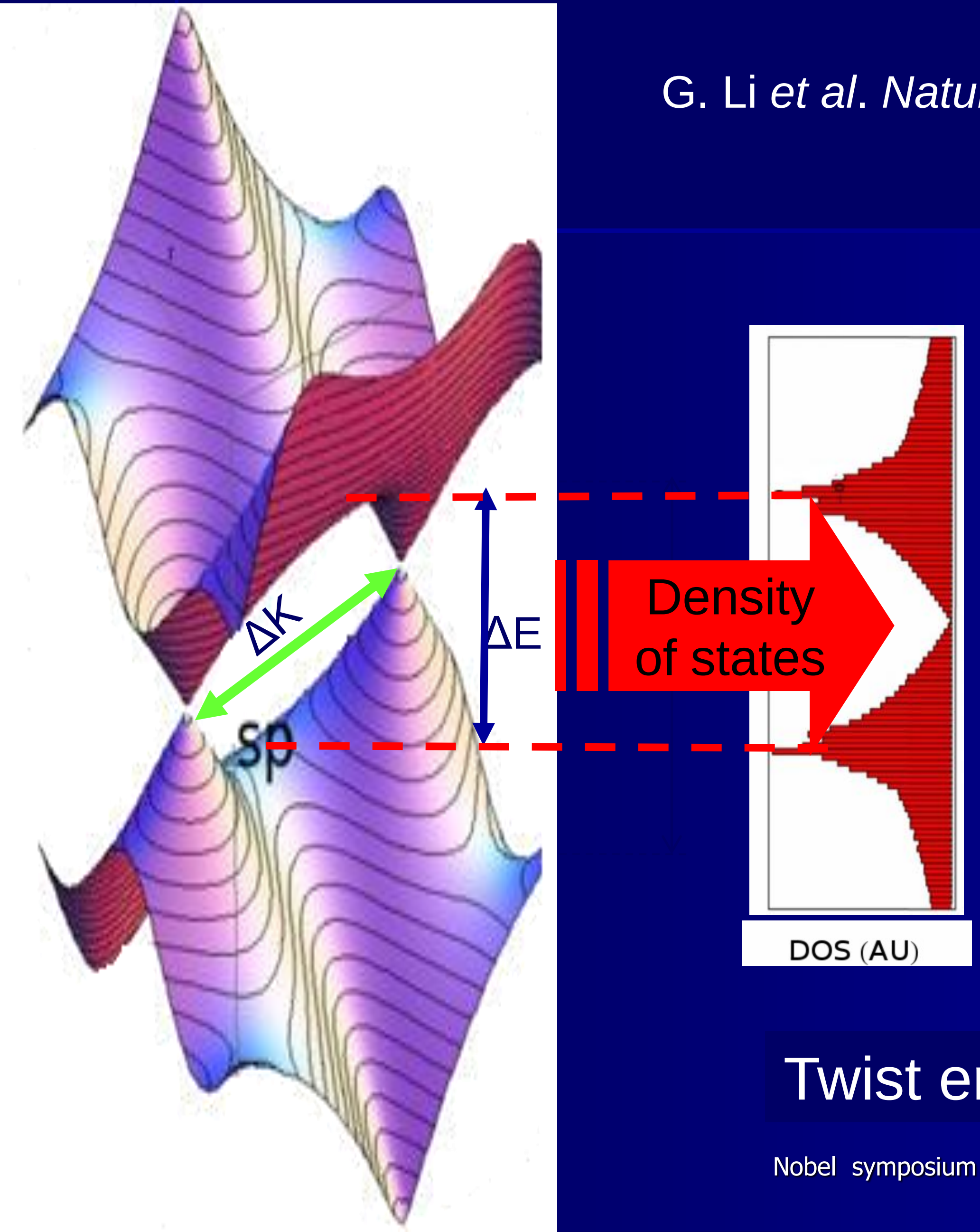
G. Li *et al*. *Nature Physics* 6, p109 (2010)

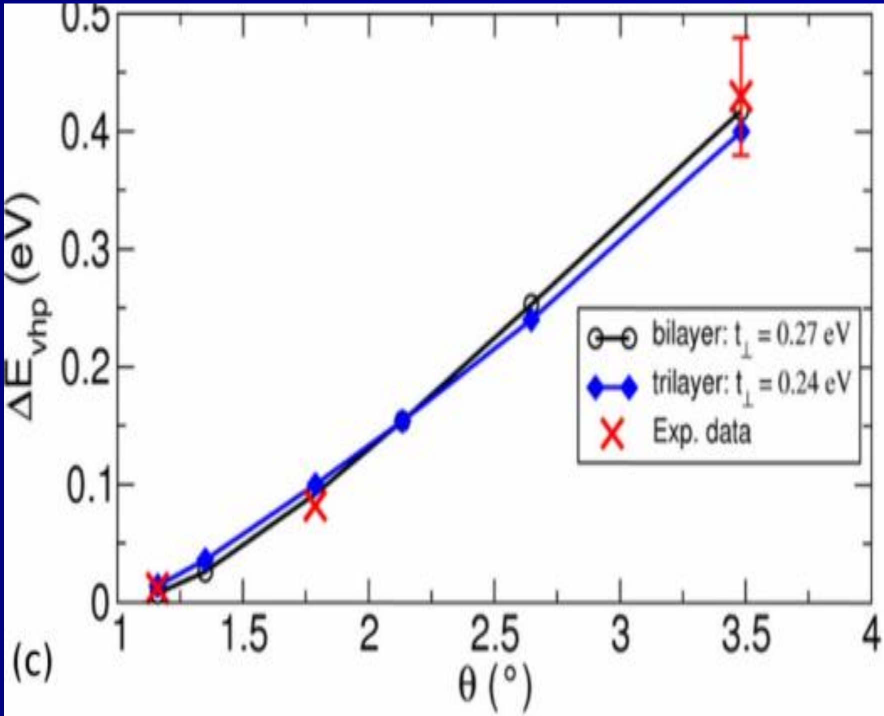




Van Hove singularities

G. Li *et al*. *Nature Physics* 6, p109 (2010)

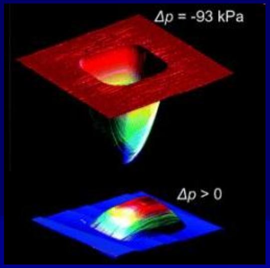


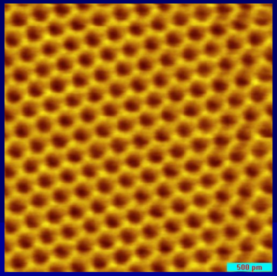


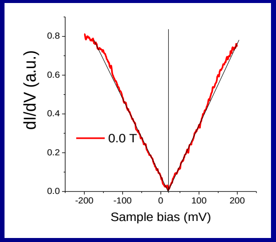
Twist engineering of electronic DOS

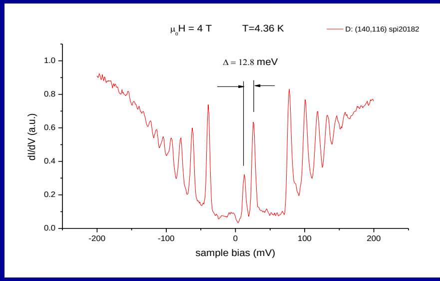
Summary

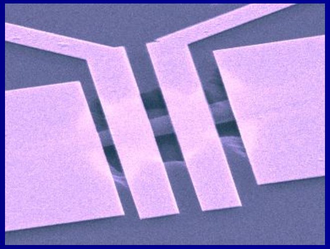
- ❑ Gee Wizz
  - Mechanical – ultra-strong, impermeable
  - Chemical – ultra-sensitive nose
  - Optical – gate controlled transmittance
- ❑ Graphene on graphite
  - Honeycomb structure
  - Dirac fermions
    - ➢ Linear Density of states
    - ➢ Well defined Dirac point
  - Direct observation of Landau levels
- ❑ Suspended graphene
  - Exfoliated membranes
    - ➢ Ballistic transport on micron length scales
    - ➢ Fractional quantum Hall effect
  - CVD membranes
    - ➢ Twist control of electronic properties

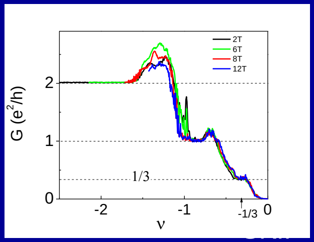


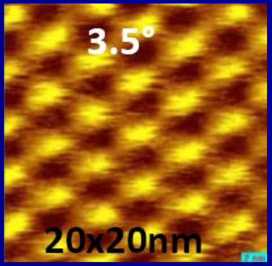


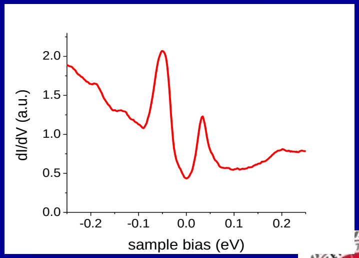












Thanks


Xu Du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Anthony Barker


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Fabian Duerr


Justin Meyerson

Collaborators:

- MIT: J. Kong, A. Reina
- Manchester: A. Geim, K. Novoselov, R. Nair
- Porto: J. los Santos
- BU: A.H. Castro Neto
- Princeton: D. Abanin
- MIT: L. Levitov