A Novel SPM System for Determining Quantum Electronic Structure at the Nanometer-scale

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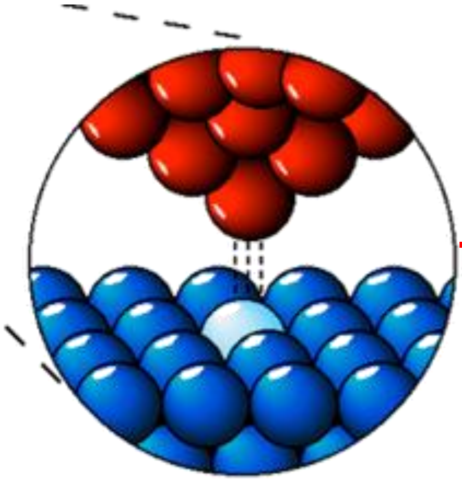
Electron Physics Group

CNST Center for Nanoscale Science & Technology

2011 Nanoelectronics Metrology, May 25, 2011

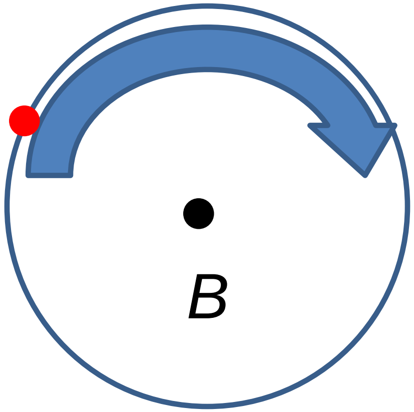
Presentation Outline

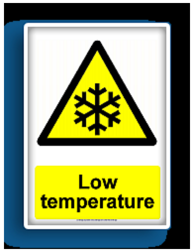
Microscopy



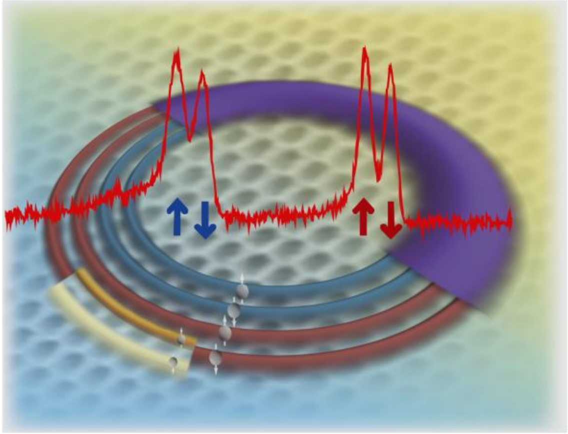
Honeycomb Lattices

Magnetic Fields

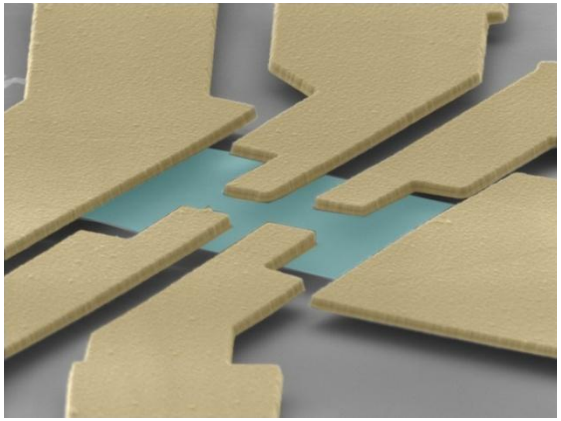




Graphene "Quartet"

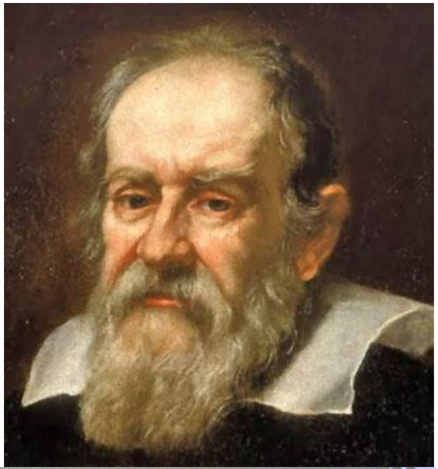


Graphene Devices

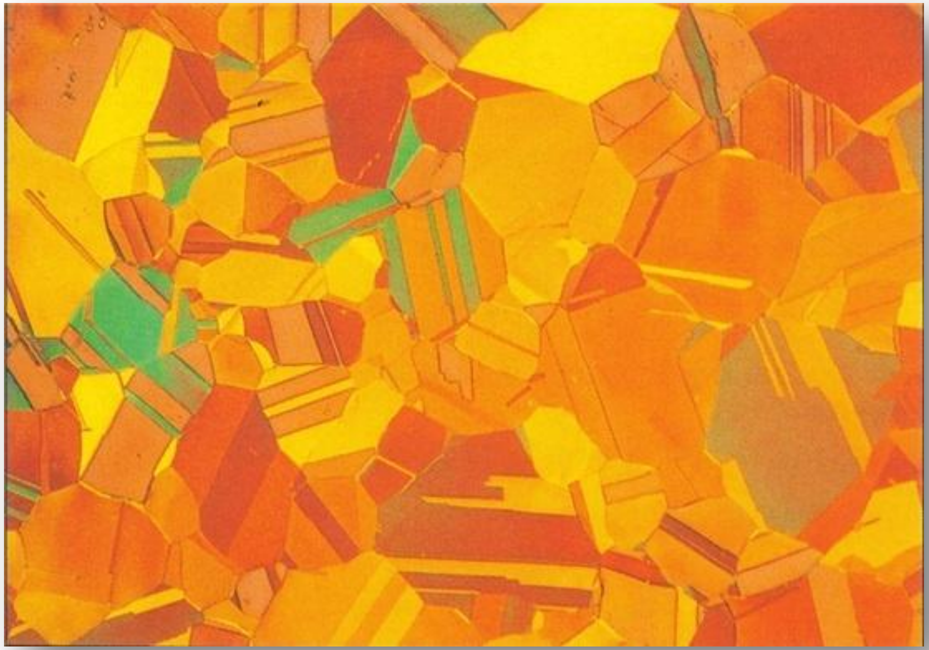


Some History of Microscopy
Occhiolino "Little Eyes" – 16th Century

- First microscope was the optical microscope
  - Compound microscopes end of 16 century
- Galileo Galilei's compound microscope in 1625
  - Occhiolino "Little Eyes"



Wikipedia

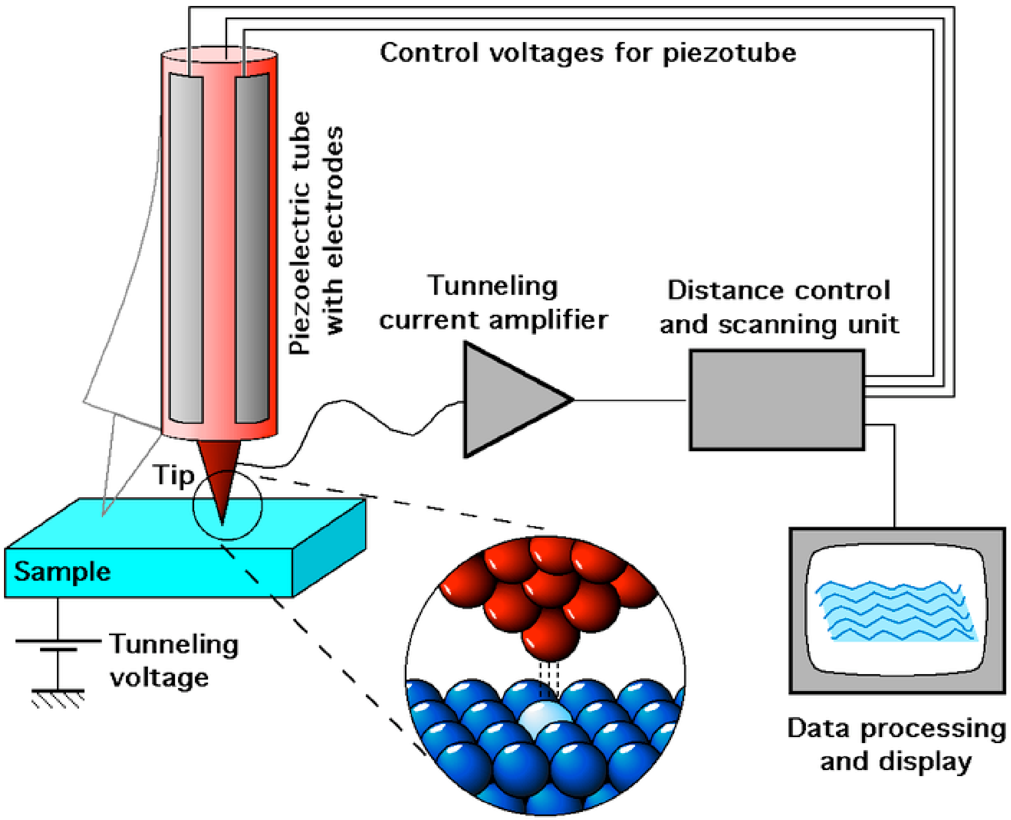


http:/www.eatechnology.com

18th century microscopes
Musée des Arts et Métiers, Paris

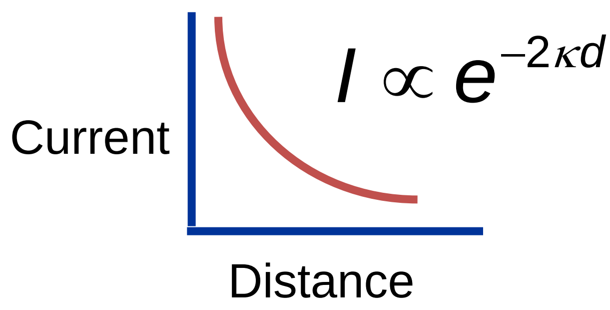
Some History of Microscopy: Scanning Tunneling Microscope a “Quantum” Microscope

- **Invented by Gerd Binnig and Heinrich Rohrer in 1981**
  - Nobel Prize in Physics in 1986 with Ersnt Ruska (electron microscope)



from Wikipedia

Quantum Mechanical Tunneling



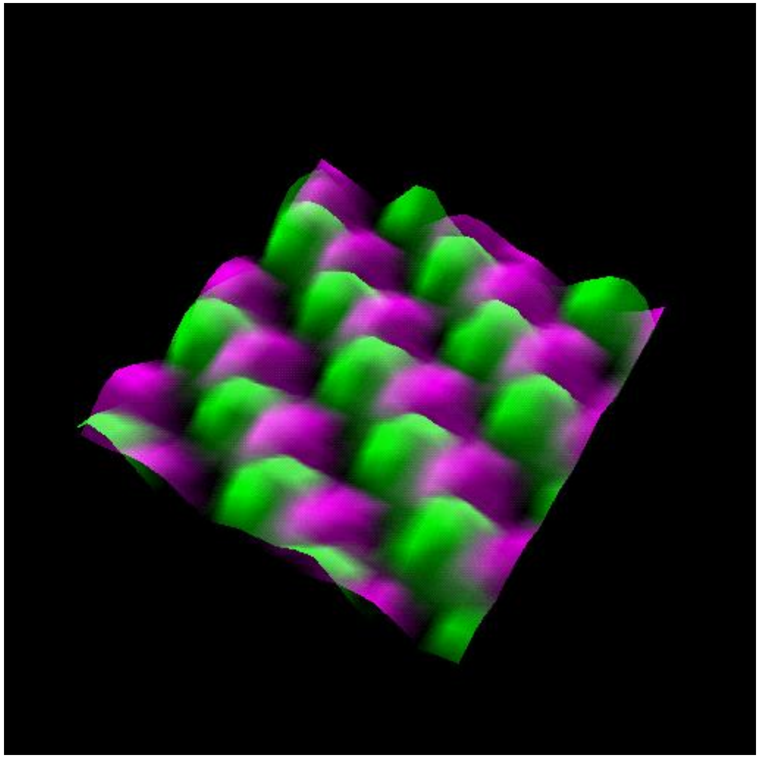
Scanning Tunneling Microscopy
A "Quantum" Microscope

STM is an electron probe, sensitive to the energy resolved local density of electron states (LDOS) – seeing in "color"

$$I \propto \int_{E_F}^{E_F+V} \rho(\vec{r}_t, E)\, T(E,V)\, dE$$

$$\rho(\vec{r}_t, E) = \sum_{\nu} \left| \psi_{\nu}(\vec{r}_t) \right|^2 \delta(E_{\nu} - E)$$

$$\frac{dI}{dV} \propto \rho(\vec{r}_t, E)\,, B\,, V_g$$



GaAs(110)

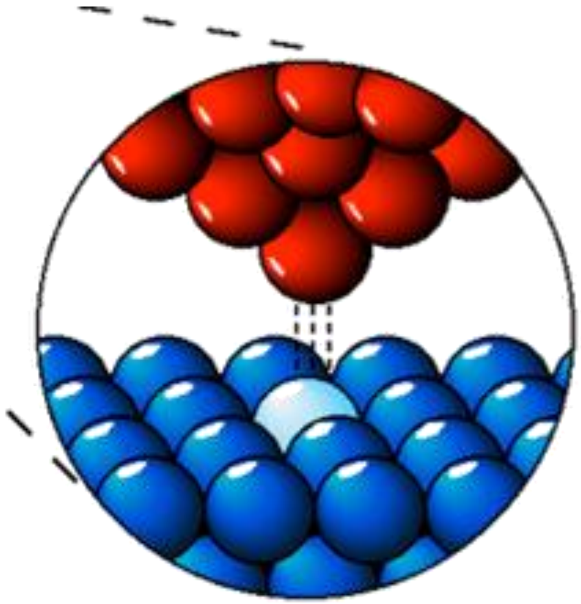
J. A. Stroscio, R. M. Feenstra, and A. P. Fein, PRL **57**, 2579 (1986)

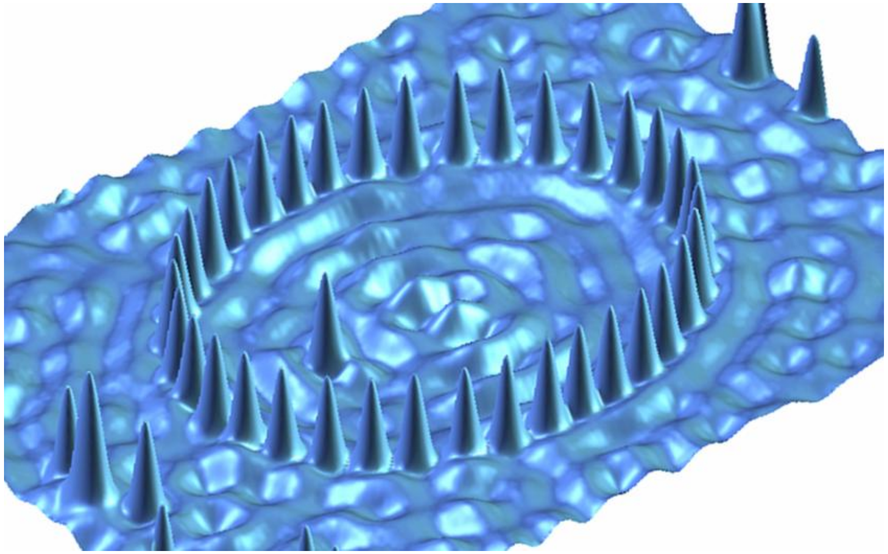
R. M. Feenstra, J. A. Stroscio, J. Tersoff, and A. P. Fein, PRL **58**, 1192 (1987)

Evolution of Cryogenic Scanning Tunneling Microscopes

- **Exponential tunneling transmission selects out the last atom on the probe tip**

- **Allows to “see”, “feel”, and “hear” in the nanometer scale world**

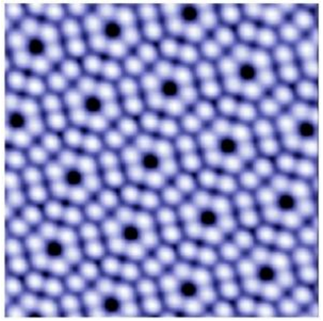




Evolution of Cryogenic Scanning Tunneling Microscopes

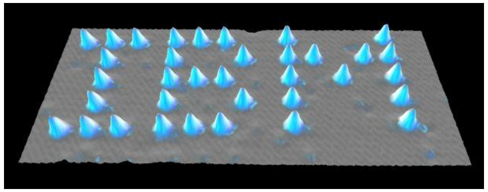
- **Desire stability and higher energy resolution**
- **Resolution limited by the thermal Fermi-Dirac distribution ~ $3k_BT$**
- **Solution: Go to lower temperatures**
  - **Not so easy!**

T = 295 K



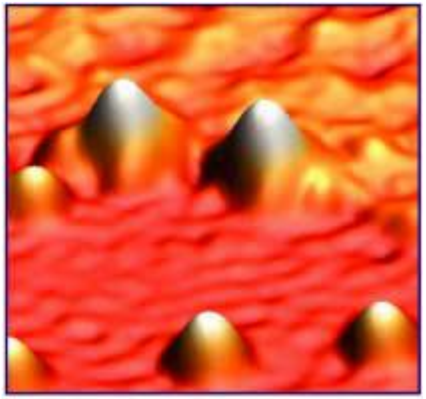
1981

T = 4 K



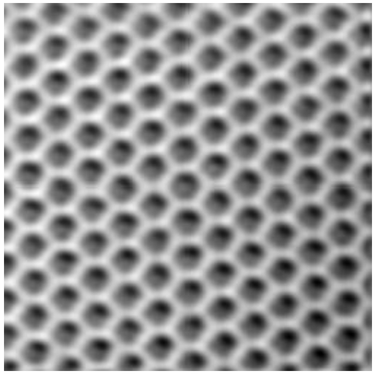
1990

T = 0.6 K



2004

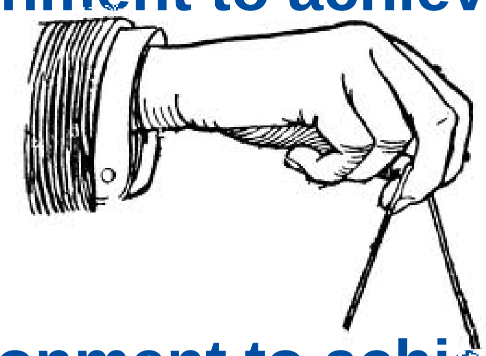
T = 10 mK

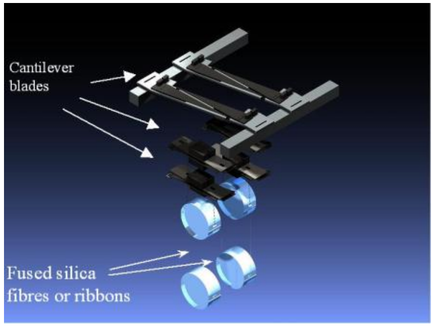


2010

Competing Requirements to Achieve High Resolution at Low Temperatures

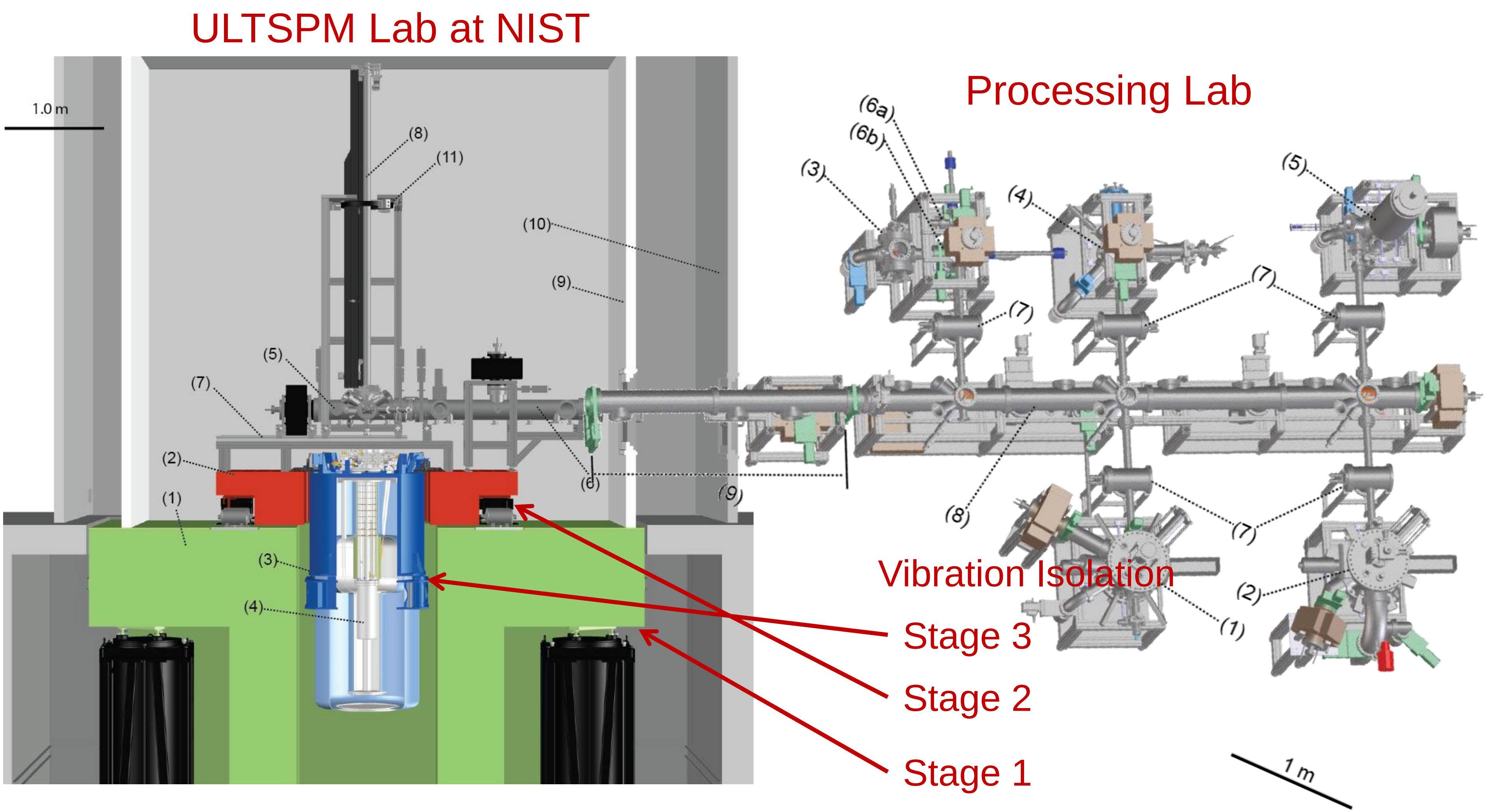
- **Tunneling current changes by x10 with 1 Å change**
  - **< 1 picometer displacement fluctuation is required**
- **Isolate from the environment to achieve small fluctuations**
  - ➢ **Poor thermal transport**





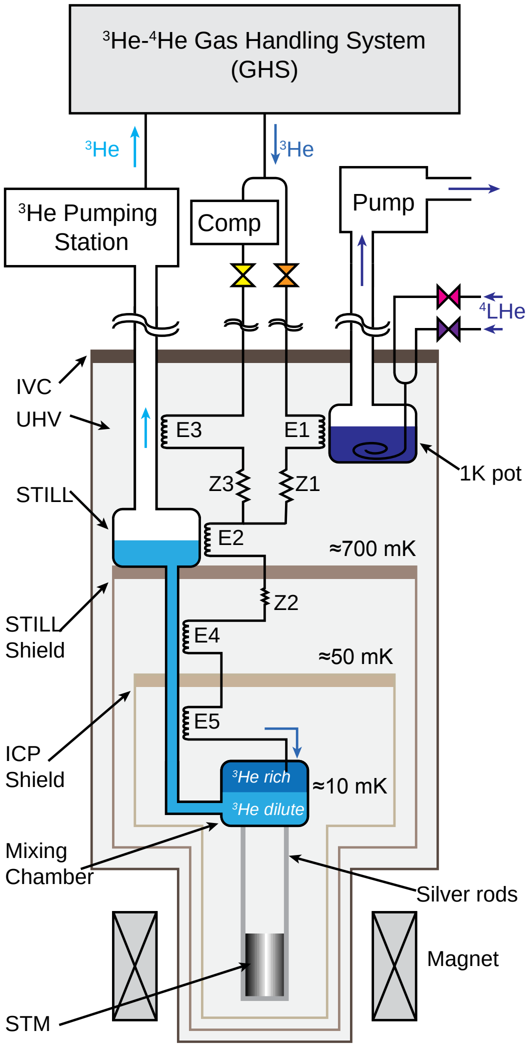
- **Bond strongly to environment to achieve good thermal contact**
  - ➢ **Poor isolation**
- **Solution is to do both!**

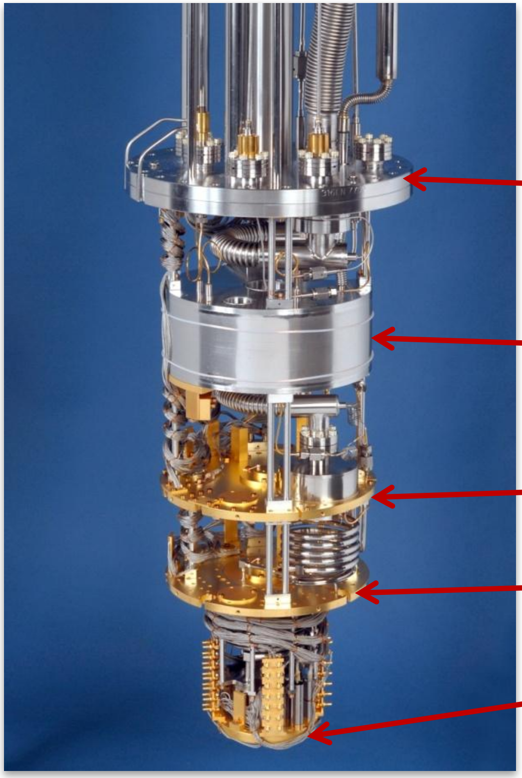
Developing High-Energy Resolution SPM Measurements



Developing High-Energy Resolution SPM Measurements

- Refrigeration to 10 mK using 3He-4He mixture





Vladimir Shvarts
Zuyu Zhao

Y. J. Song *et al*. RSI (2010)

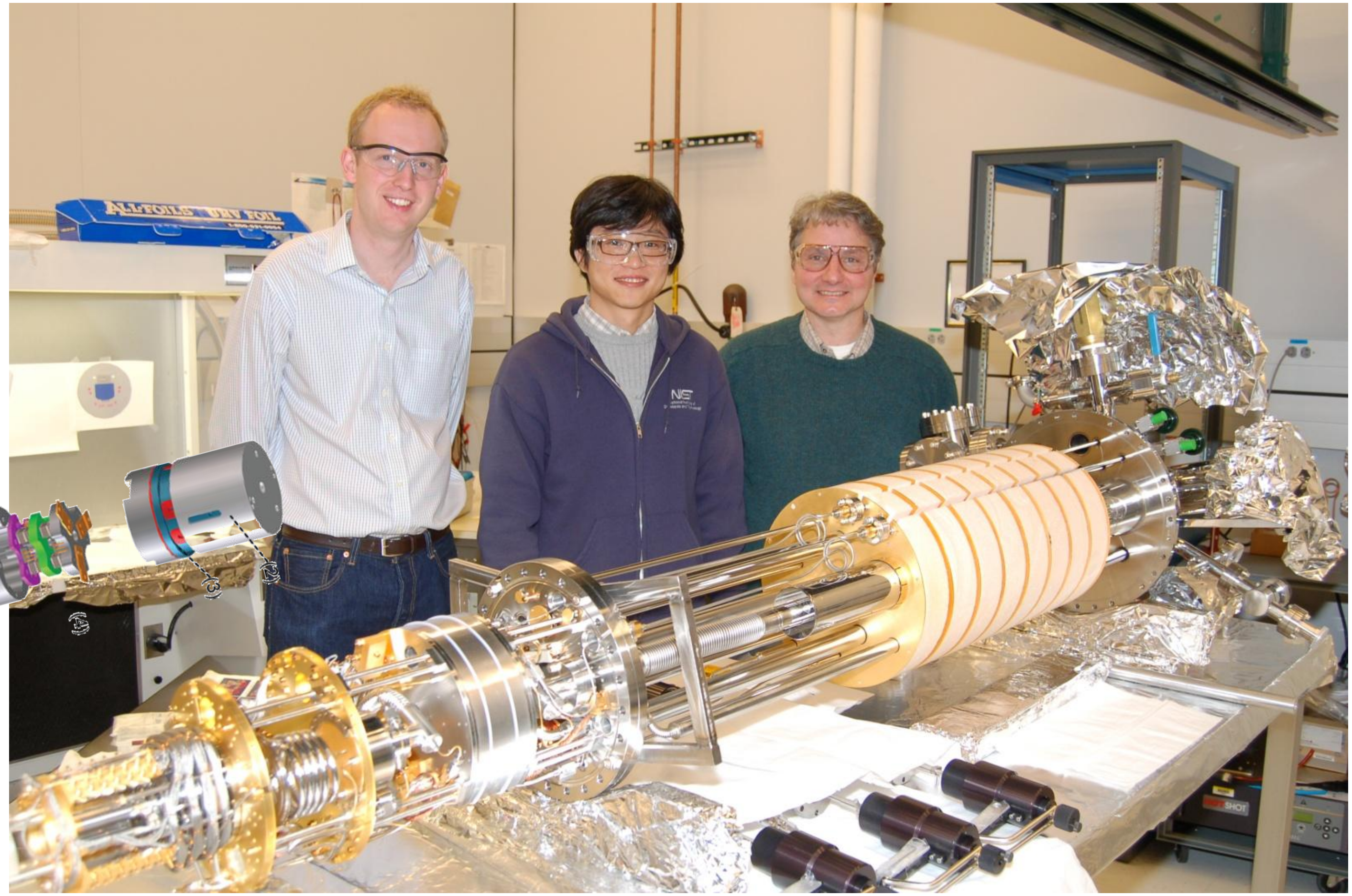
Developing High-Energy Resolution SPM Measurements

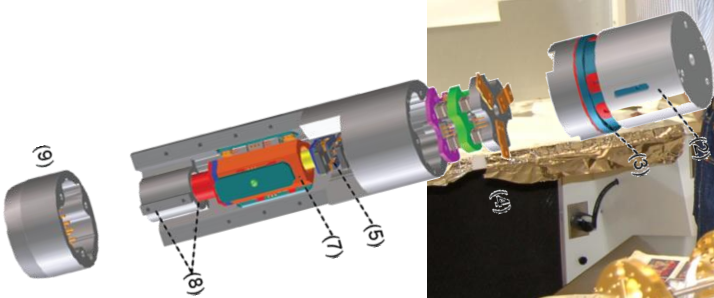
Young Jae Song

Alexander F. Otte

Young Kuk

Joseph A. Stroscio

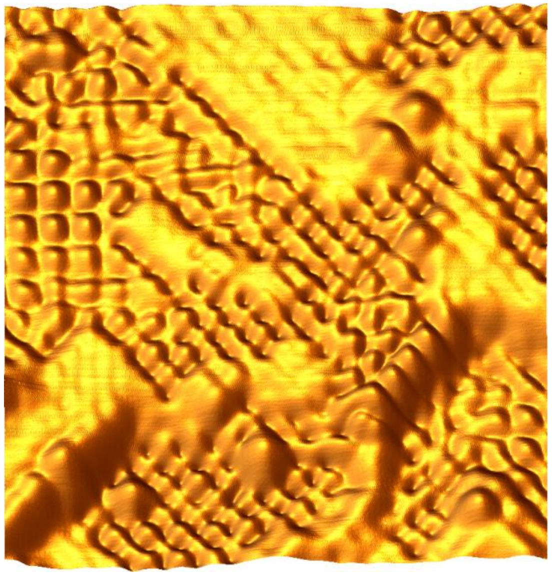




Developing High-Energy Resolution SPM Measurements

- **Excellent performance down to lowest temperatures**
- **JT is better than 1K pot**
  - **Z noise < 1 pm $Hz^{1/2}$**
  - **I noise < 100 fA $Hz^{1/2}$**

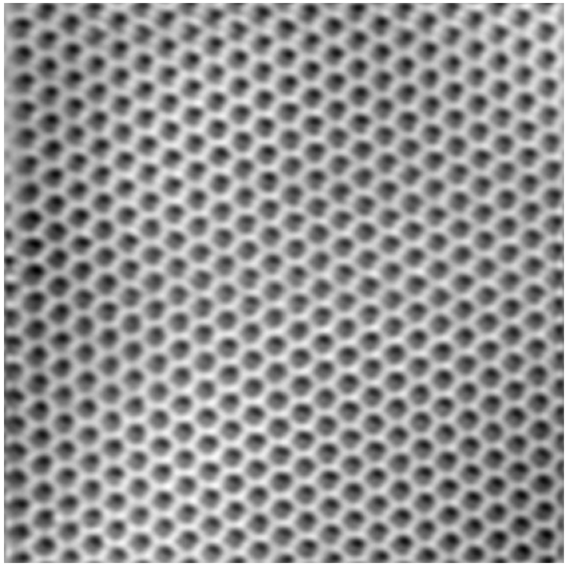
Er atoms on CuN



8 nm

Graphene/SiC

T=13 mK



5 nm

Y. J. Song *et al*. RSI (2010)

Presentation Outline

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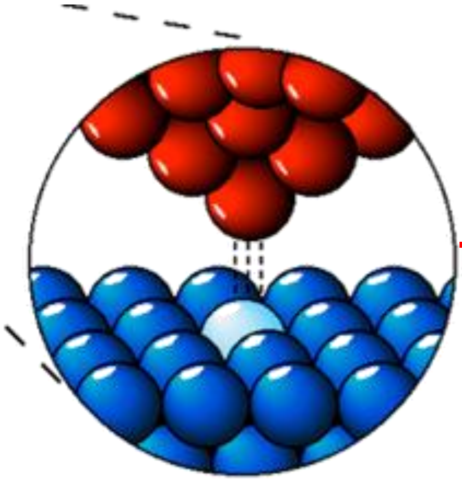

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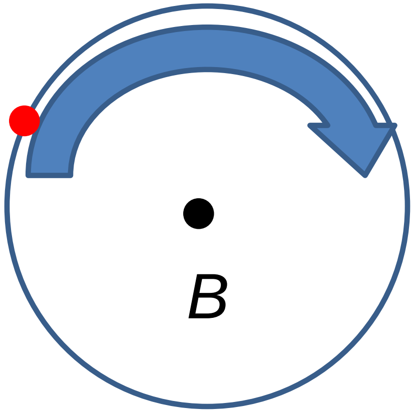
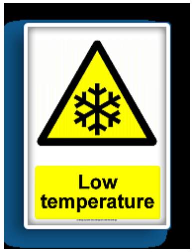
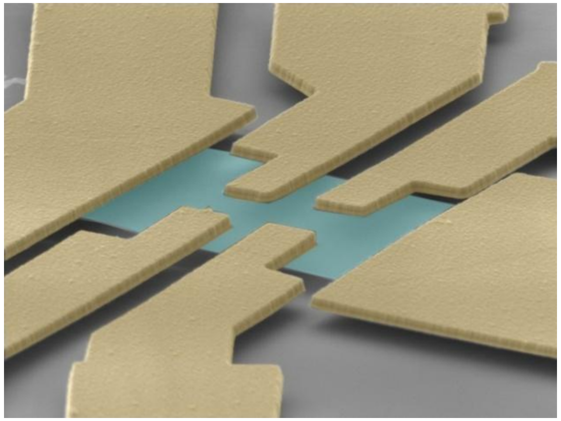
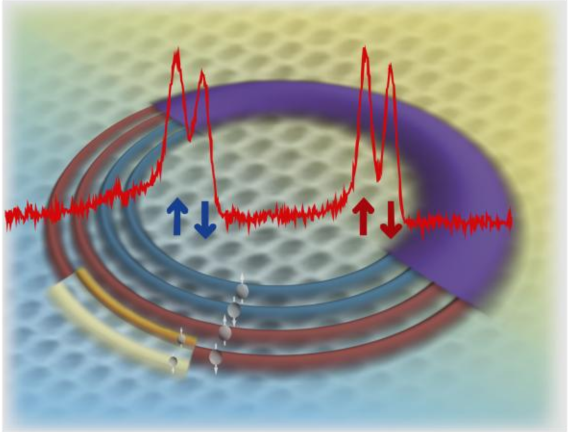




Graphene Devices



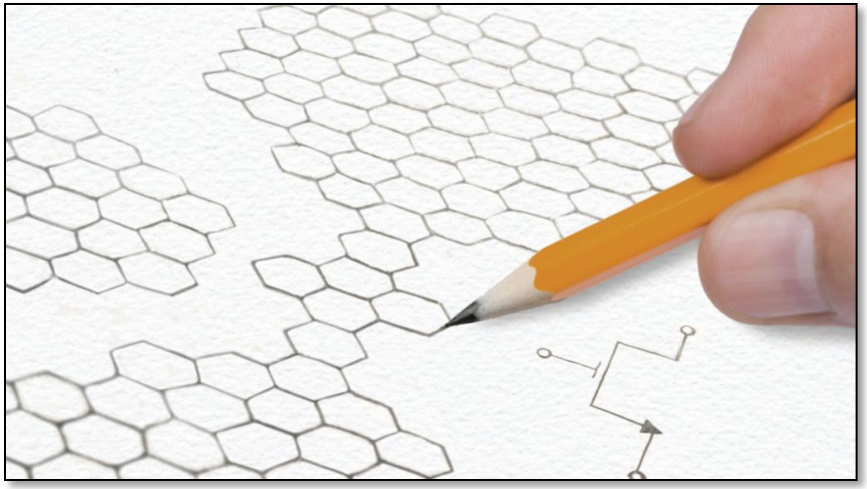
Graphene "Quartet"



From Honeycombs to the Dirac Hamiltonian

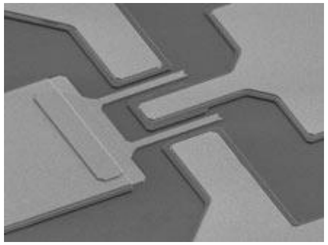
Graphene – Light-like Electrons

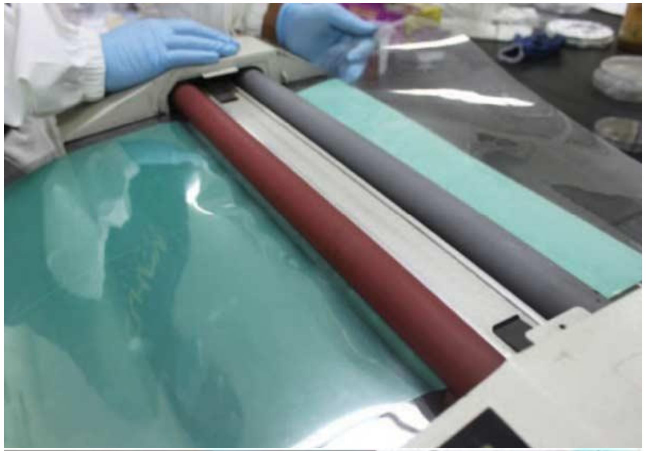
From Pencil Drawings to High Speed Transistors to iPAD? Or Galaxy Tab?



Savage, N., "Researchers pencil in graphene transistors." *IEEE Spec.* 45, 13 (2008).

IBM and HRL GHz Transistors

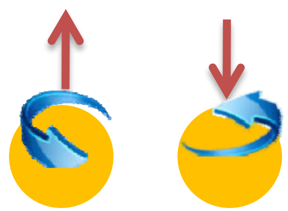




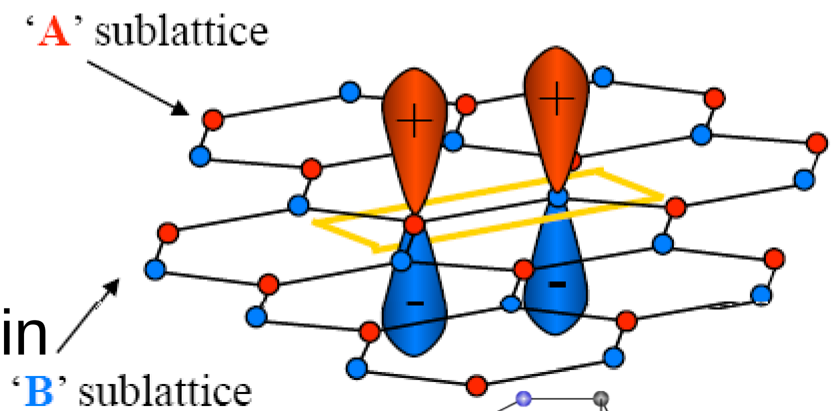
New Materials and State Variables

- Graphene, TIs; Spin and Pseudo-Spin as State Variables

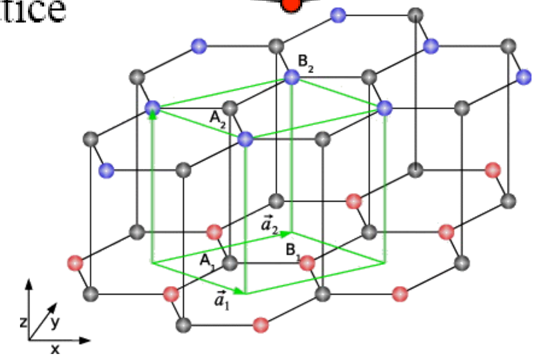
- Electron spin



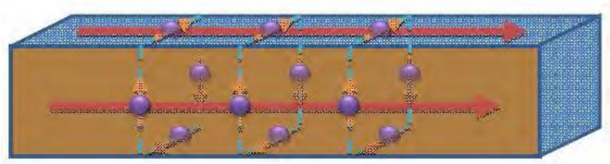
- Graphene sub-lattice pseudo-spin



- Graphene bilayer – layer pseudo-spin



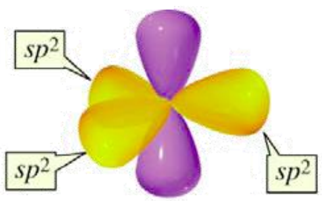
- Topological Insulator – spin locked to momentum



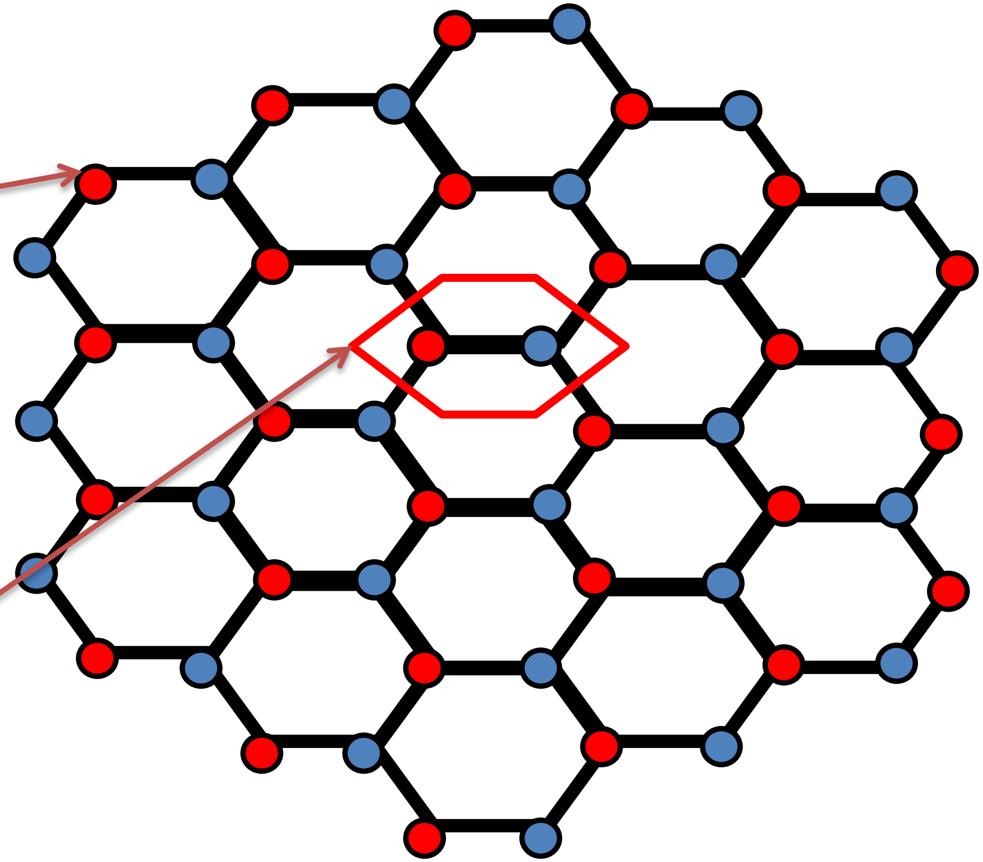
Graphene Dirac Fermions

Graphene Basics

Carbon with 4 valence electrons



Two atom basis in the unit cell
→ pseudo-spin



Top View (real space)

From Honeycombs to the Dirac Hamiltonian

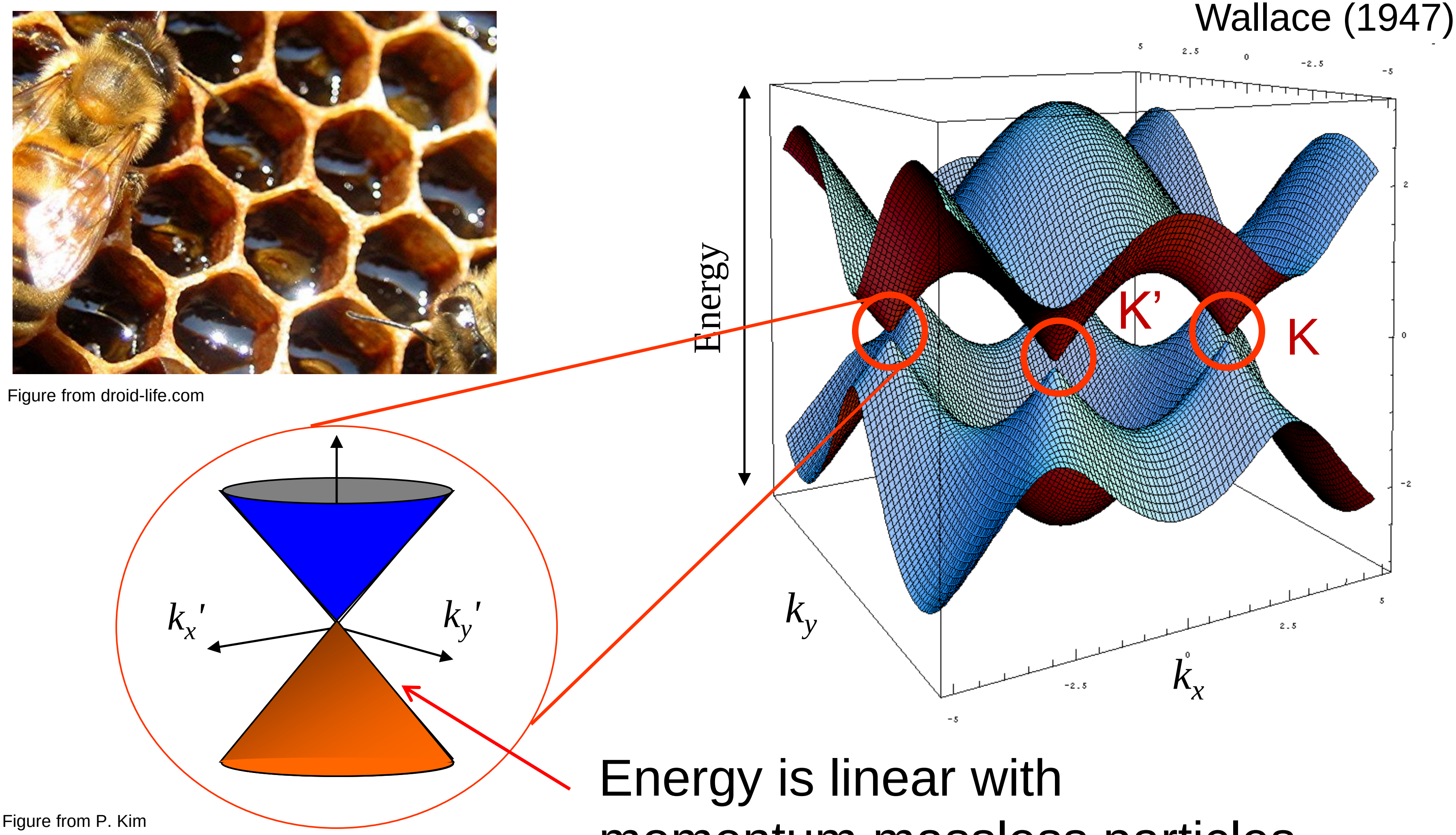


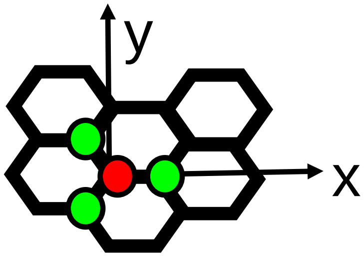
Figure from droid-life.com

Figure from P. Kim

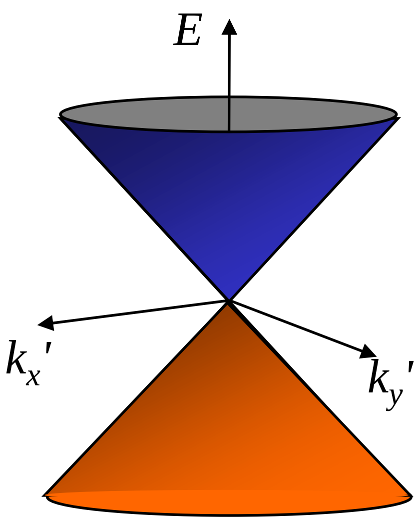
Energy is linear with momentum massless particles

Low Energy Expansion: Dirac Hamiltonian

Real space:



Reciprocal space:



For behavior away from Dirac point, make an expansion:

$$K \rightarrow K + \delta K = \left(0, \frac{4\pi}{3a}\right) + \left(k_y, k_x\right)$$

$$v_F = \frac{\sqrt{3}a}{2}\gamma_{nn}$$

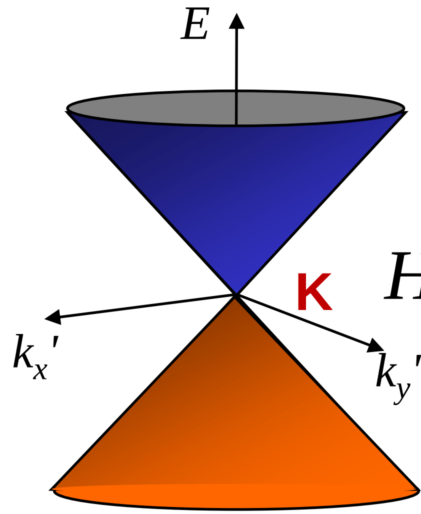
$$H_{\mathbf{K}} = v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} = v_F \boldsymbol{\sigma} \cdot \mathbf{k}$$

$$E = \pm v_F k \qquad \psi_{\pm,\mathbf{K}}(\mathbf{k}) = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-i\theta_{\mathbf{k}}/2} \\ \pm e^{-i\theta_{\mathbf{k}}/2} \end{pmatrix}$$

$$\theta_{\mathbf{k}} = \arctan\left(\frac{k_x}{k_y}\right)$$

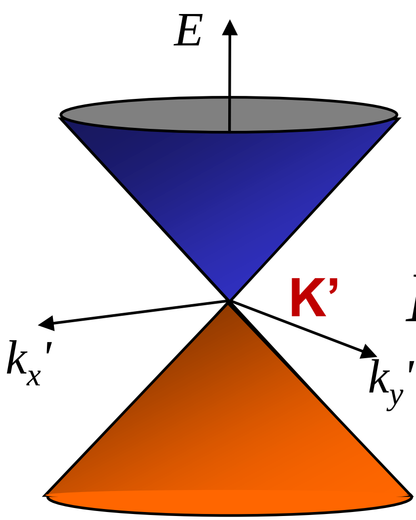
Paul Dirac

The Independent Two Valleys



$$H_{\mathbf{K}} = v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix}$$

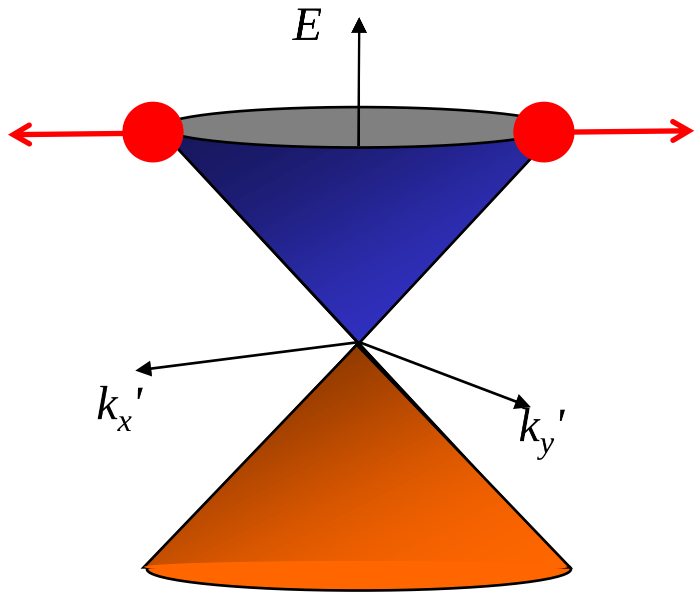
Leads to additional degeneracy



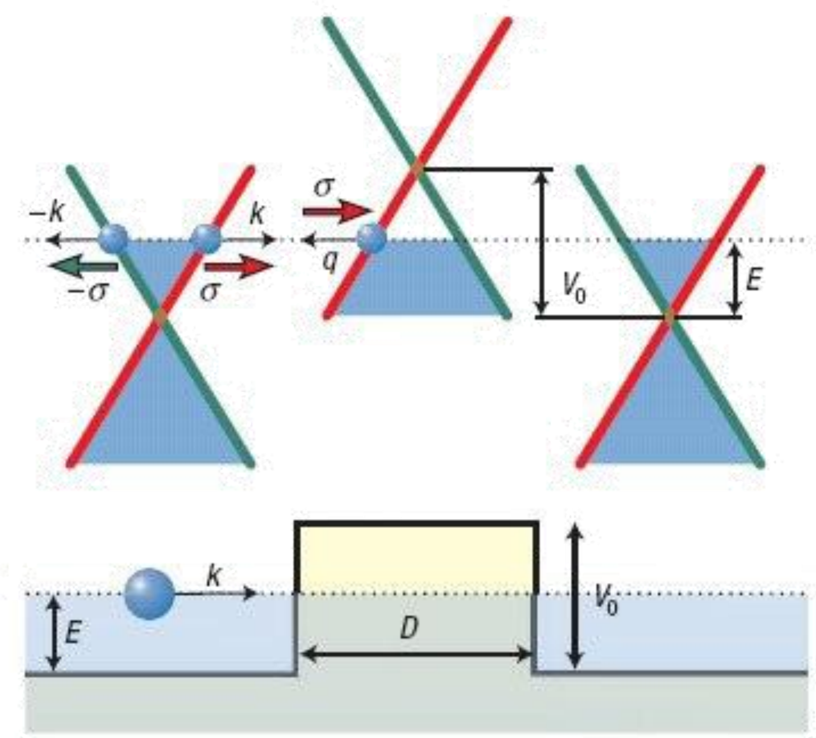
$$H_{\mathbf{K}'} = v_F \begin{pmatrix} 0 & k_x + ik_y \\ k_x - ik_y & 0 \end{pmatrix}$$

Consequences of Dirac Hamiltonian

Pseudo-spin; reduced backscattering



Klein tunneling; transmission through potential barriers



Katsnelson et al. Nature Physics 2006

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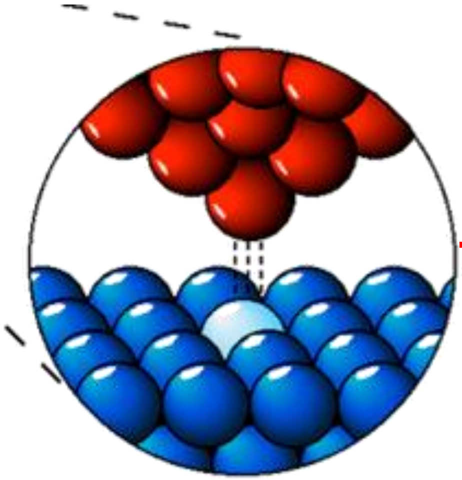

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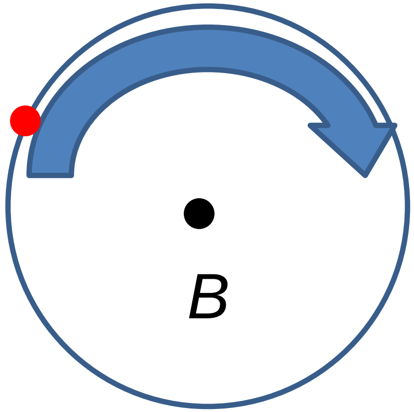

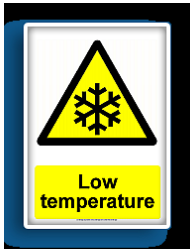

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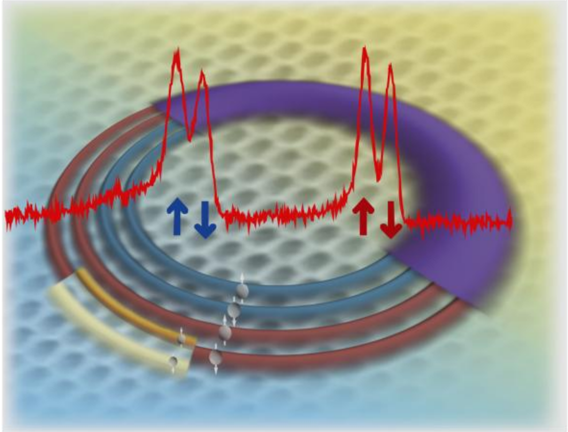

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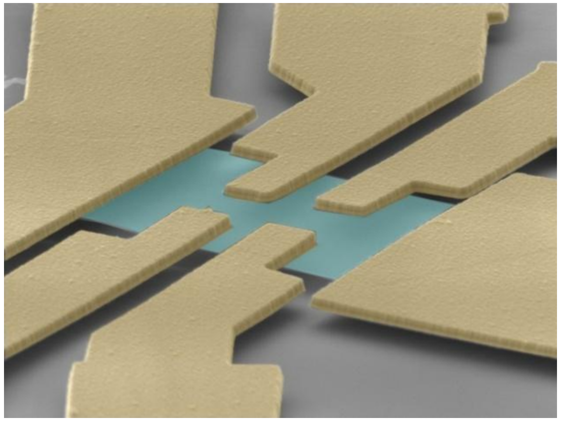
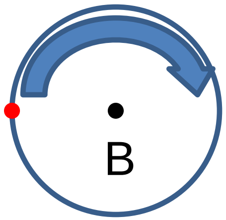
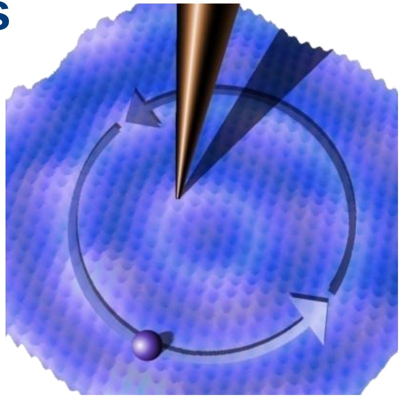


Landau Quantization in Graphene

- **Cyclotron motion in a magnetic field**
  - **Quantized orbits and energy levels**



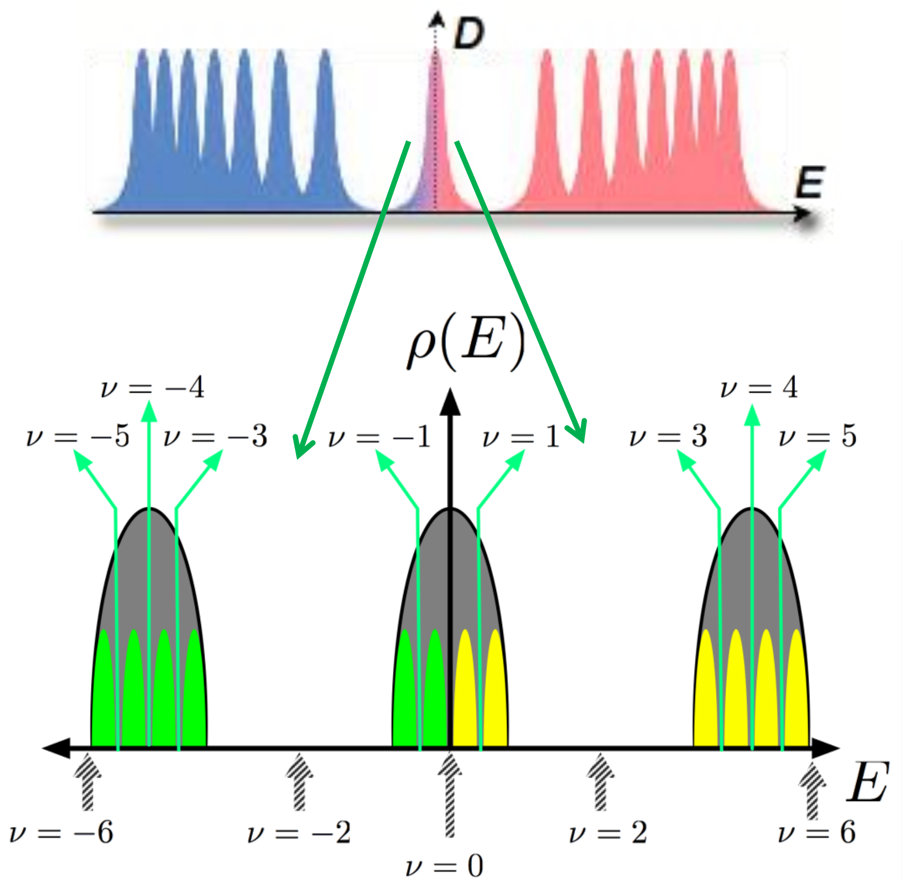
- Scattering in the graphene landscape
- Effects of disorder and interactions



Lev Landau
1908 - 1968

Landau Quantization in Graphene

The Graphene Quartet



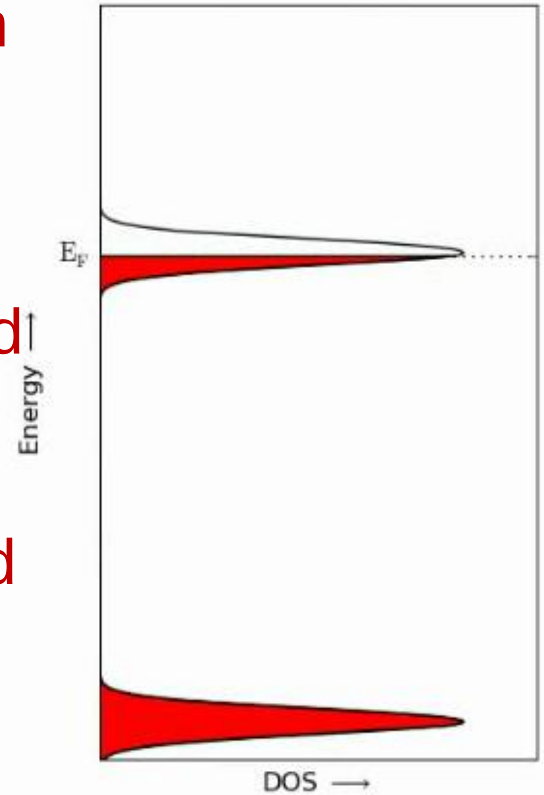
- Four-fold degenerate due to spin and valley symmetries
- STS provides direct measure of energy gaps and interaction effects

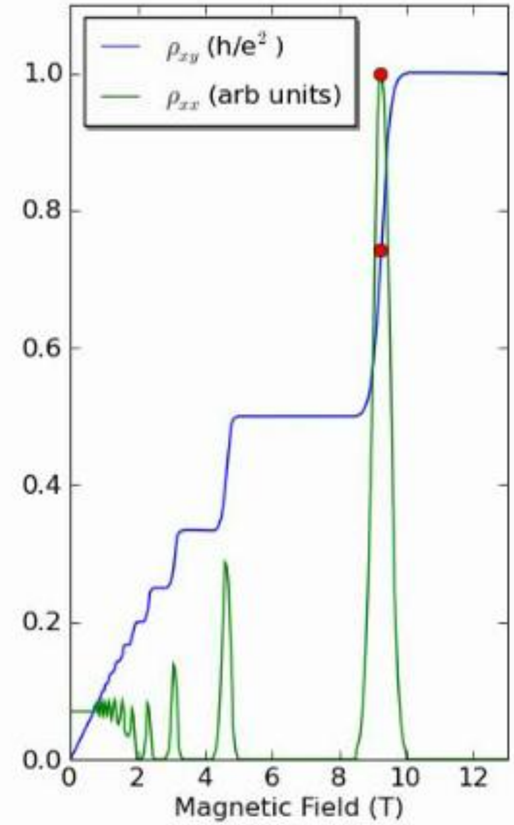
STS vs Transport Measurements

STS

Transport

- Wide energy spectrum
- Localized states in the mobility gaps
- Spatial properties of extended and localized states
- Energy gaps when degeneracies are lifted
- Correlation effects





http://en.wikipedia.org/wiki/Quantum_Hall

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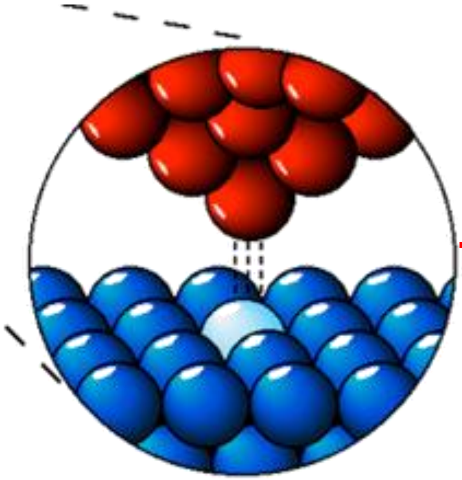

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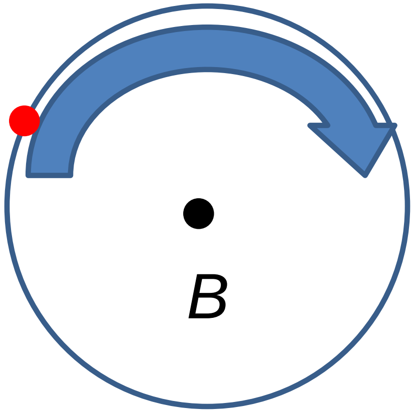

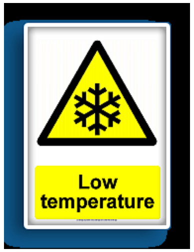

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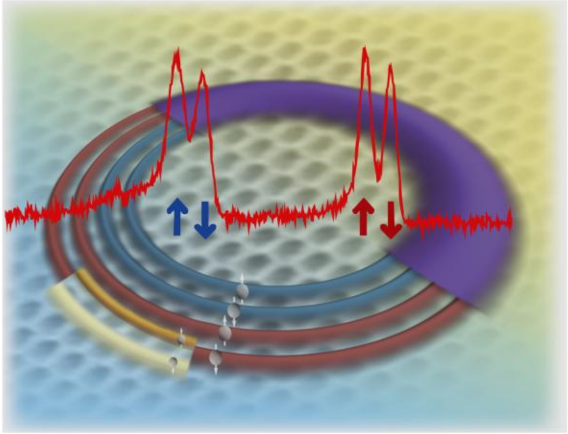
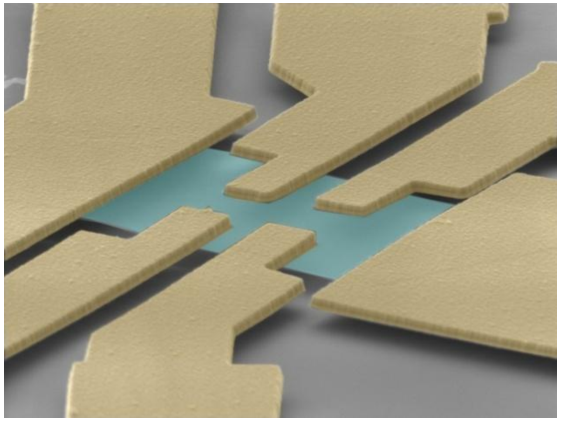
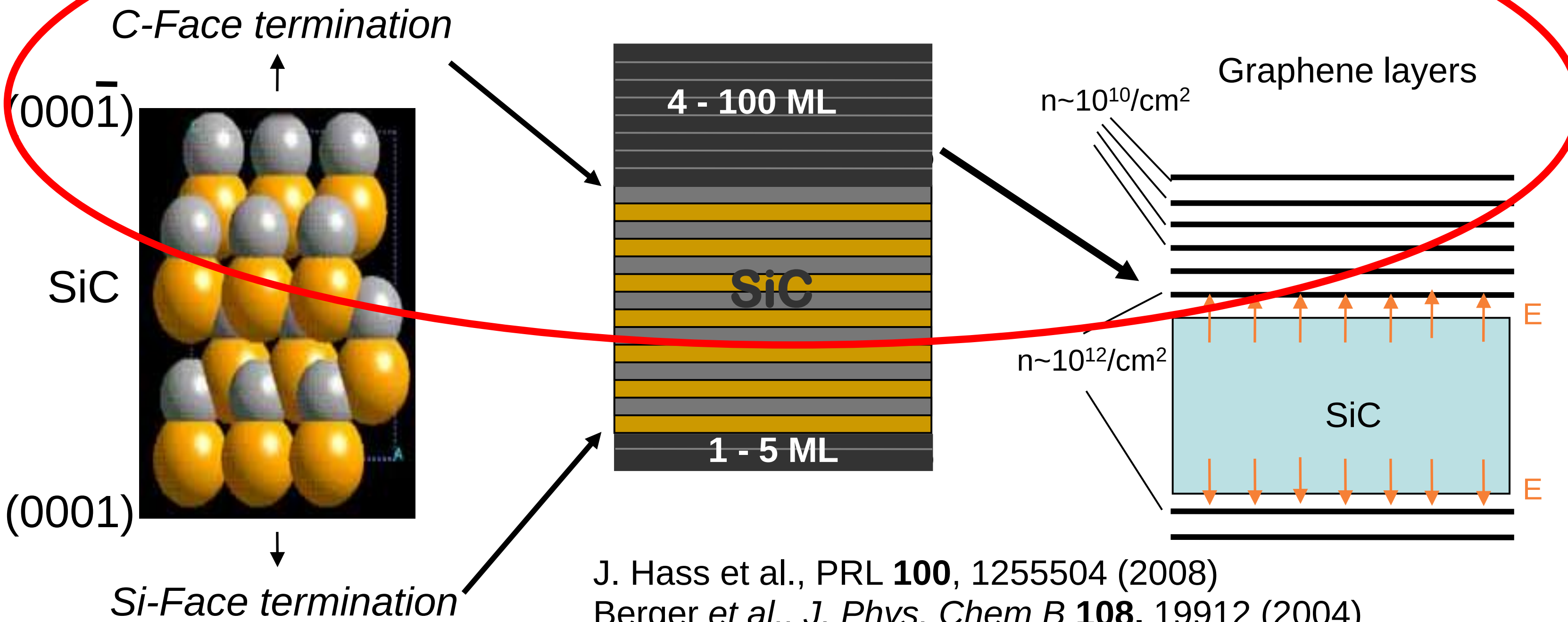


Graphene Devices



Epitaxial Graphene on C-face SiC – Weak Disorder

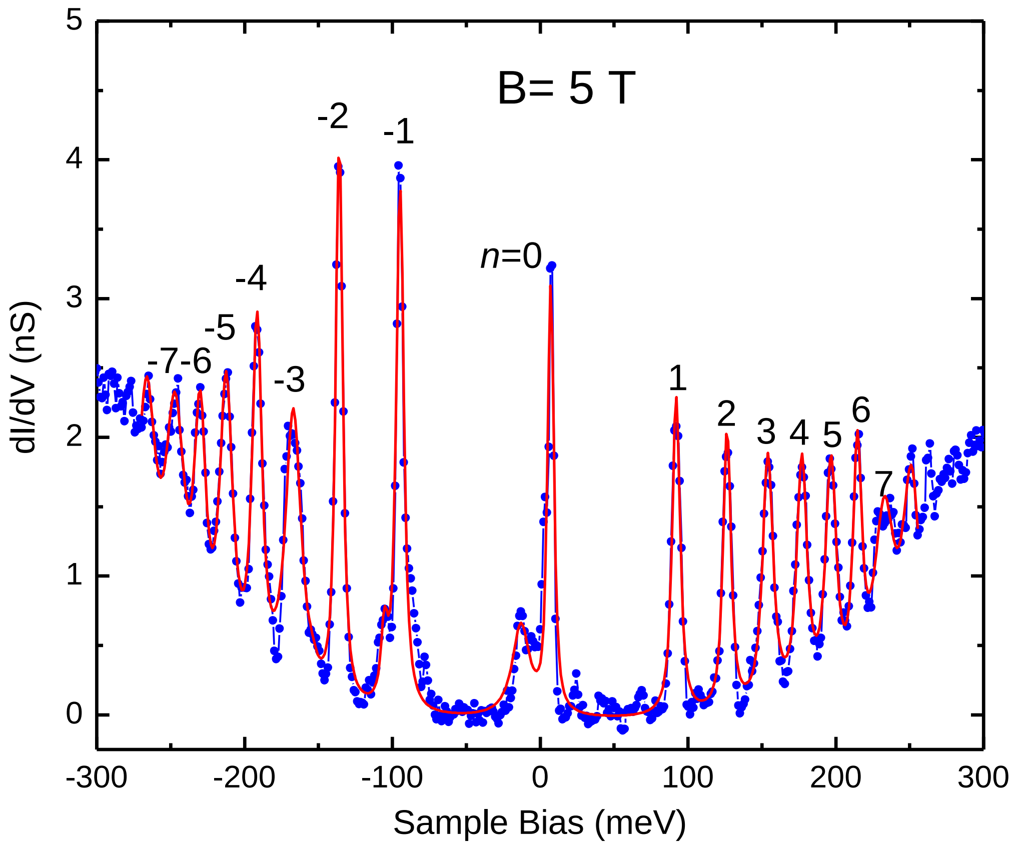
Induction Furnace Method



J. Hass et al., PRL **100**, 1255504 (2008)
Berger *et al., J. Phys. Chem B* **108,** 19912 (2004)
Berger *et al., Science* **312,** 1191 (2006)
de Heer *et al., Sol. St. Commun.,* **143**, 92 (2007)

Magnetic Quantization C-face Graphene at 4K

- **Direct measurement of graphene quantization**
- **Weak disorder**

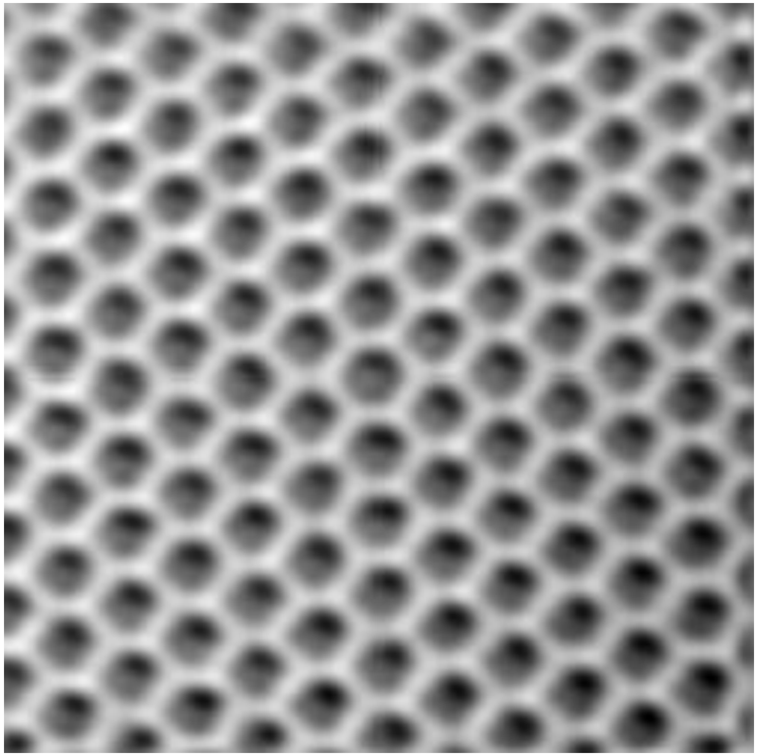


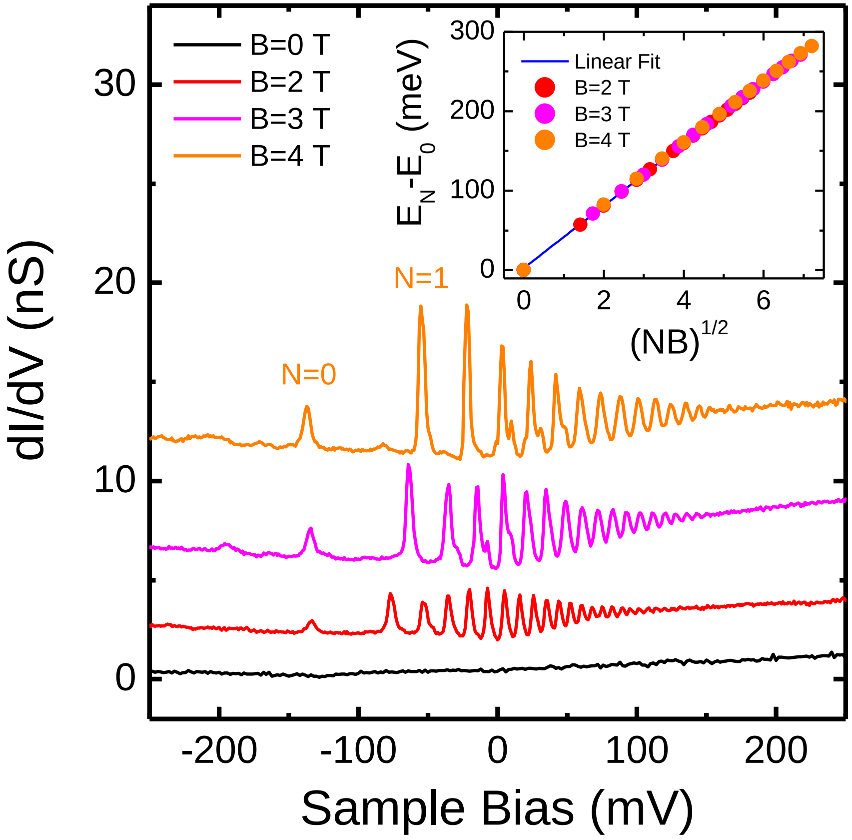
- Quantization obeys graphene scaling
- Full quantization of DOS into Landau levels
- Very sharp LLs
- High mobility

D. L. Miller, *et al*., *Science* **324**, 924 (2009).

Resolving the Graphene Quartet

Tunneling Spectroscopy at ~10 mK





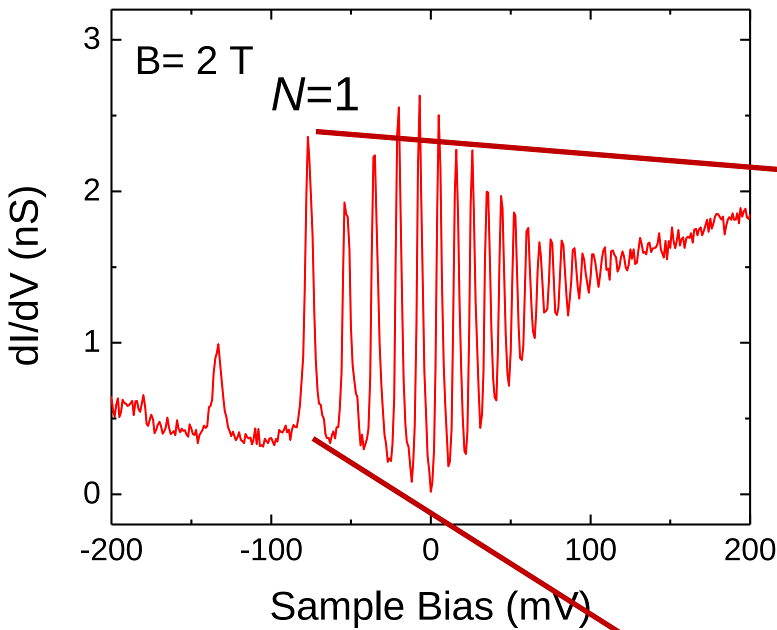
Graphene on C-face SiC

Zero field Dirac point is at -125 meV indicating a doping of ~1 x 10^{12} cm^{-2}

Y. J. Song *et al*. Nature (2010)

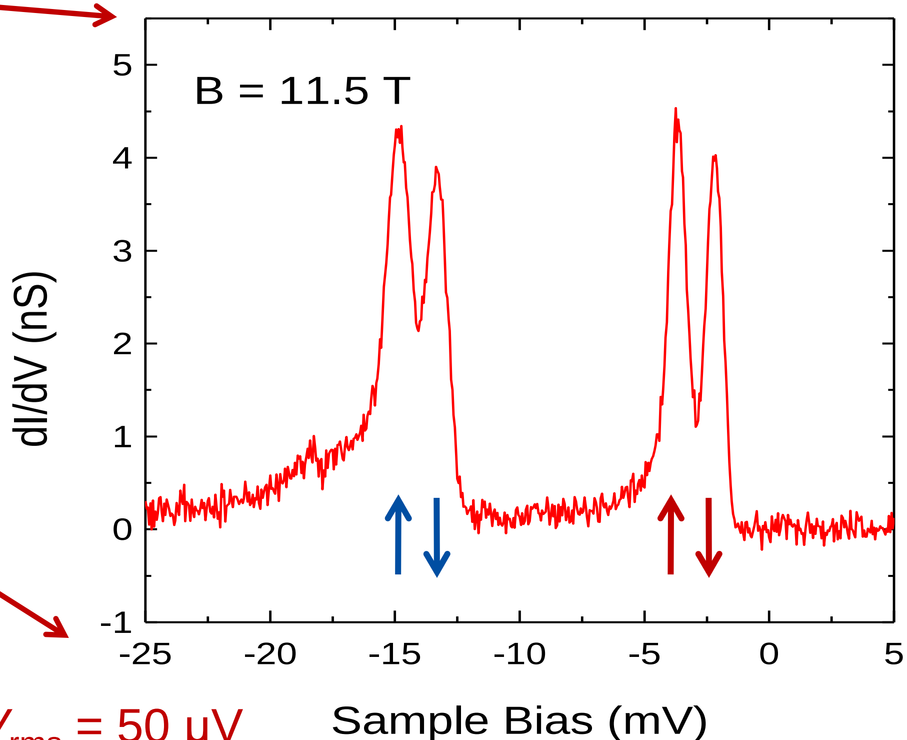
Resolving the Graphene Quartet

Tunneling Spectroscopy at ~10 mK



ΔV_{rms} = 1 mV

Weak disorder in graphene on C-face SiC allows fine features to be observed



ΔV_{rms} = 50 µV

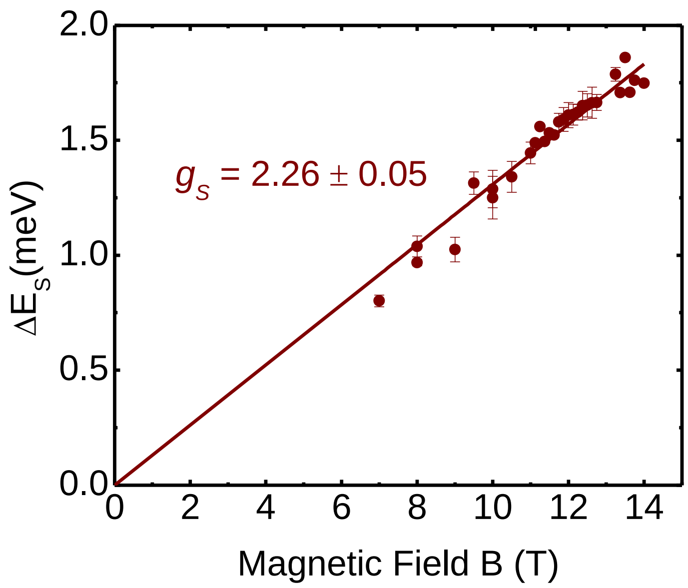
Y. J. Song *et al*. Nature (2010)

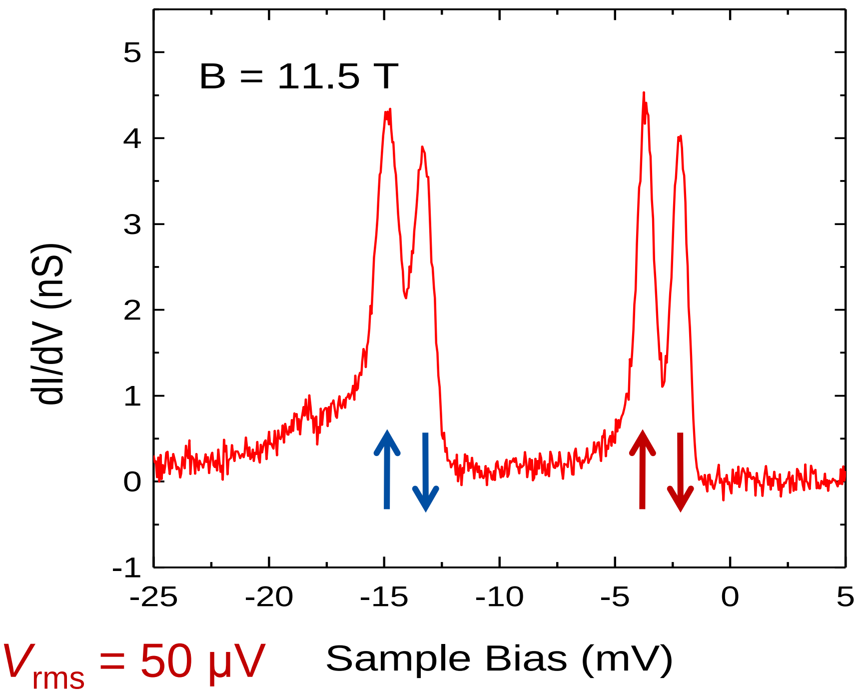
Resolving the Graphene Quartet

Tunneling Spectroscopy at ~10 mK

Smaller peak separation – electron spin?

Weak disorder in graphene on C-face SiC allows fine features to be observed





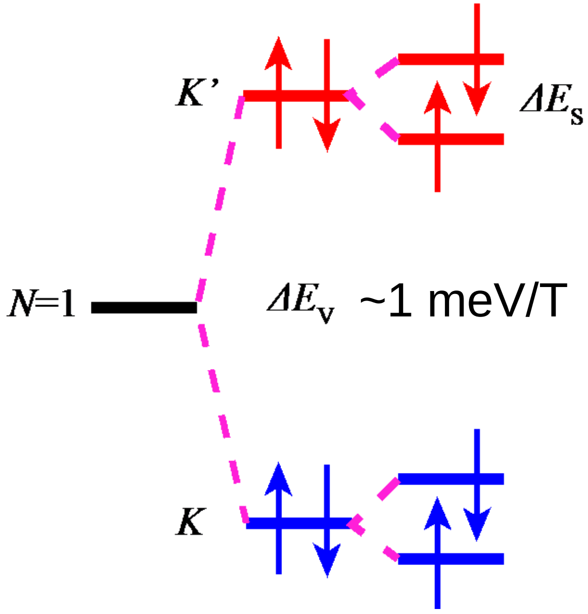
ΔV_{rms} = 50 μV

Y. J. Song *et al*. Nature (2010)

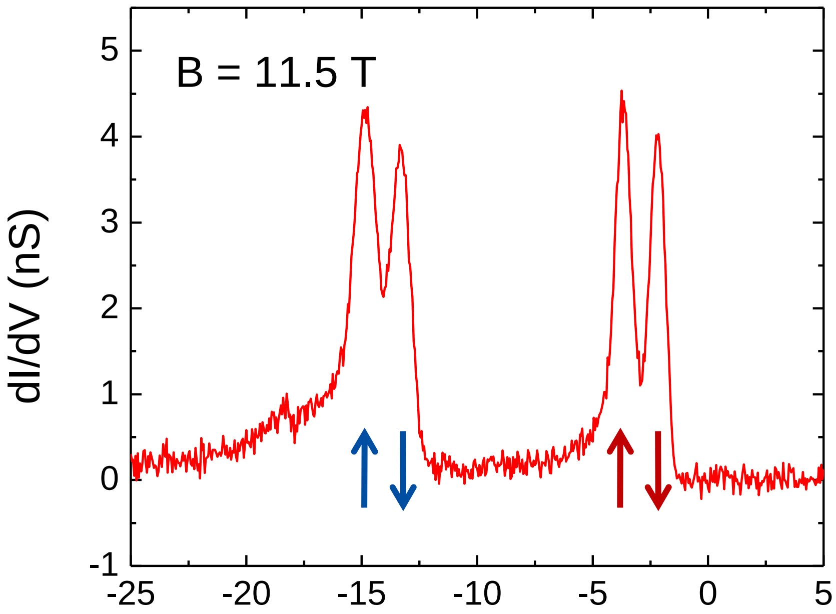
Resolving the Graphene Quartet

Tunneling Spectroscopy at ~10 mK

Valley splitting is ten times larger than smaller energy splitting



Weak disorder in graphene on C-face SiC allows fine features to be observed

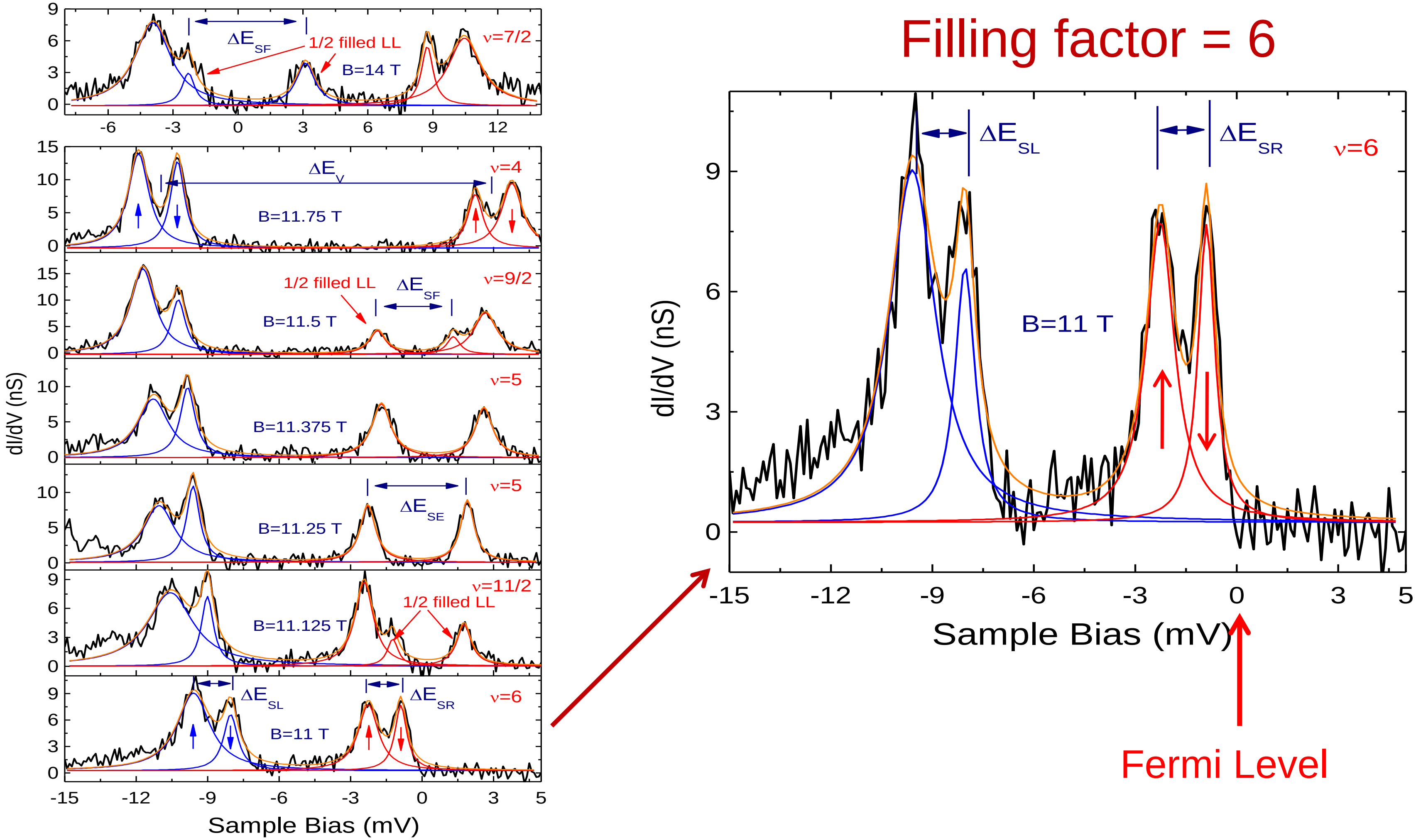


ΔV_{rms} = 50 μV

Y. J. Song *et al*. *Nature* (2010)

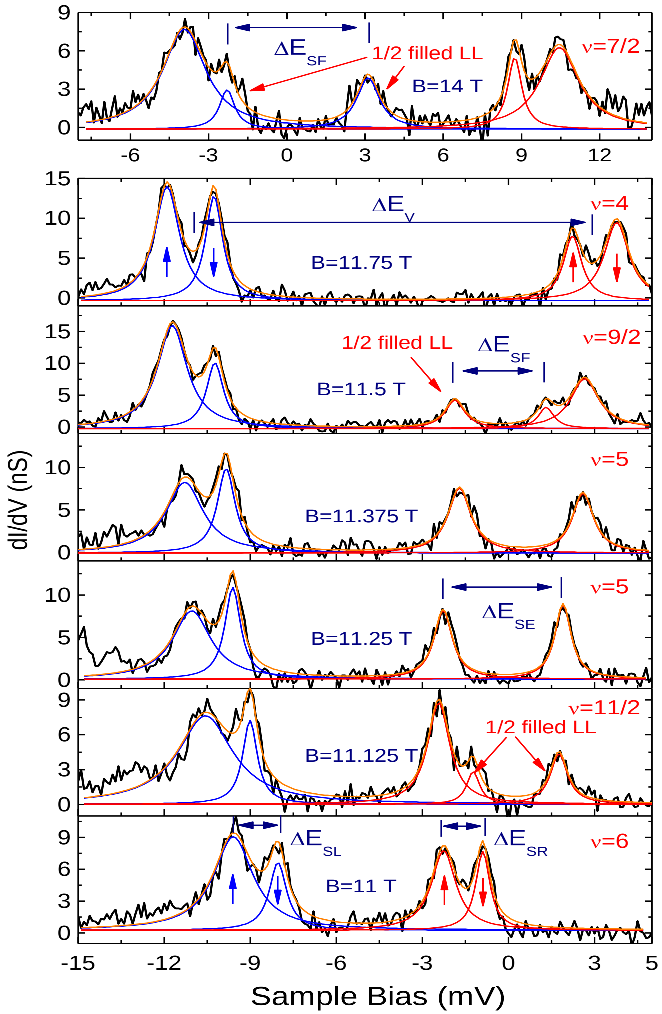
Many Body Effects in Graphene

Polarizing Landau Levels

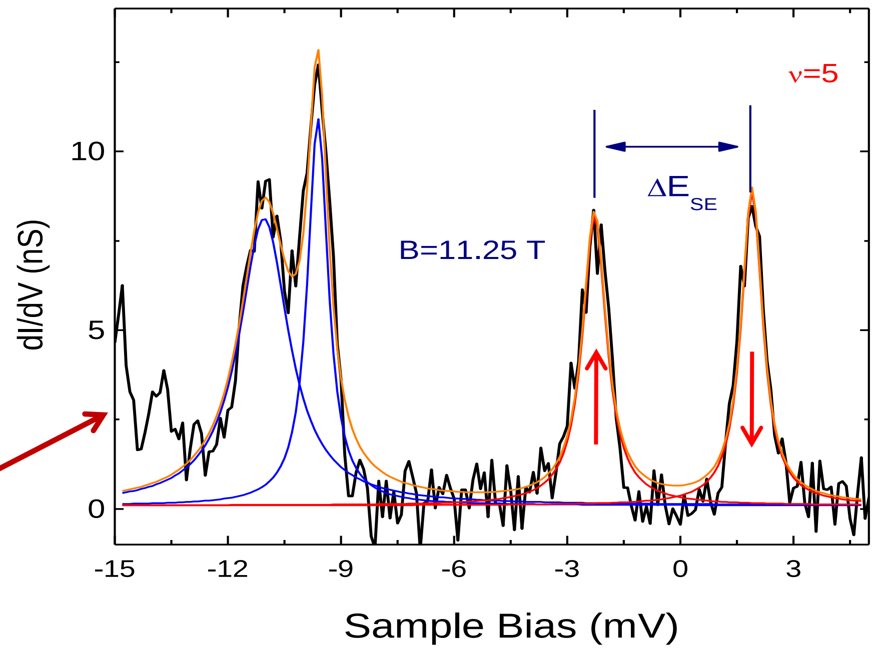


Many Body Effects in Graphene

Polarizing Landau Levels



Filling factor = 5

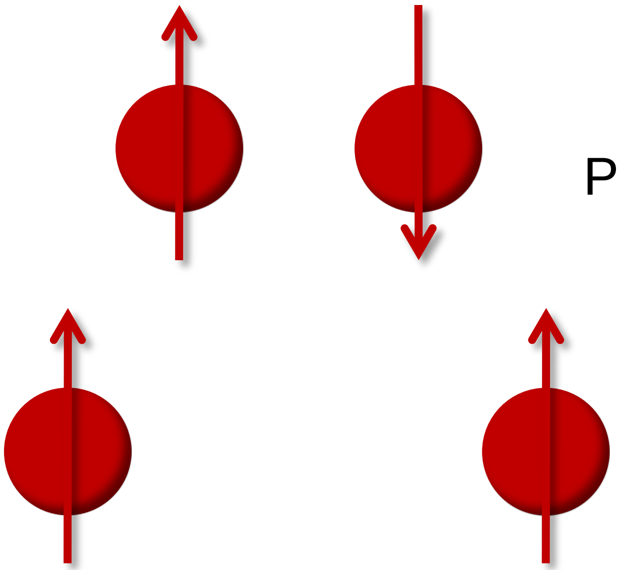


Enhanced spin splitting at odd filling factors

Enhanced valley splitting at *ν*=4

Many Body Effects in Graphene

- **Enhanced Exchange Interaction**
- **For polarized LL, symmetric spin and antisymmetric space wavefunction leads to enhanced exchange interaction**



Pauli Exclusion Principle

Wolfgang Pauli

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, Vol. 37, No. 4, OCTOBER, 1974

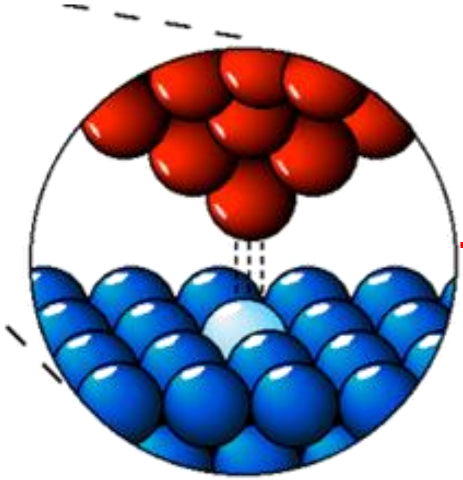
Theory of Oscillatory g Factor in an MOS Inversion Layer under Strong Magnetic Fields*

Tsuneya ANDO and Yasutada UEMURA
Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113

(Received May 14, 1974)

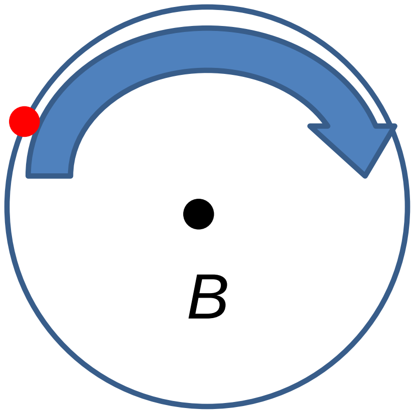
Presentation Outline

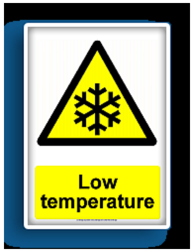
Microscopy



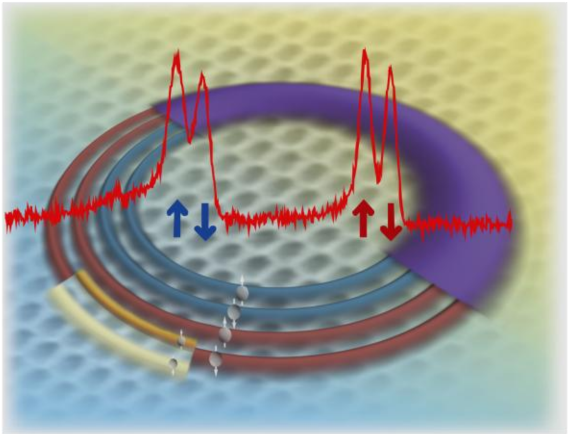
Honeycomb Lattices

Magnetic Fields

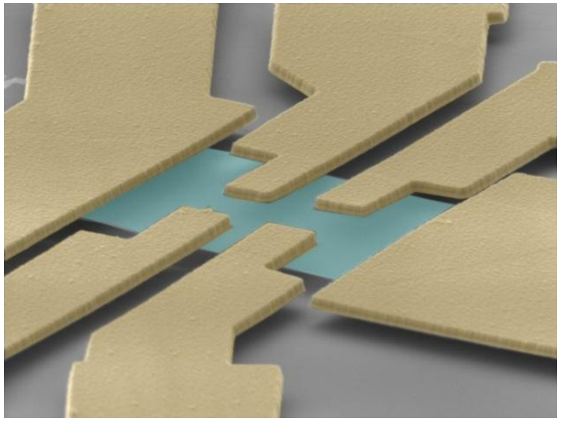




Graphene“Quartet”

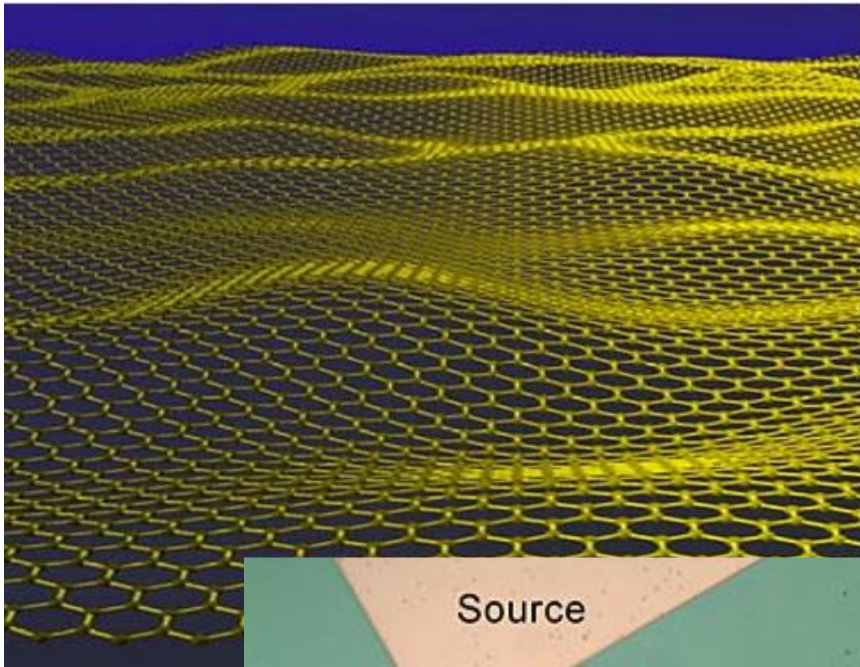


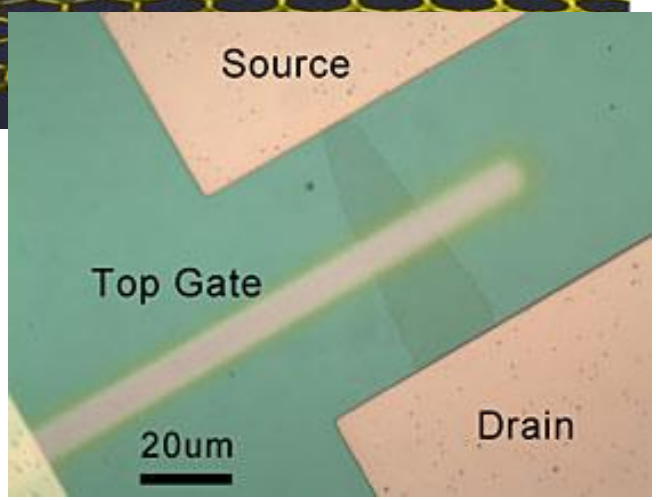
Graphene Devices



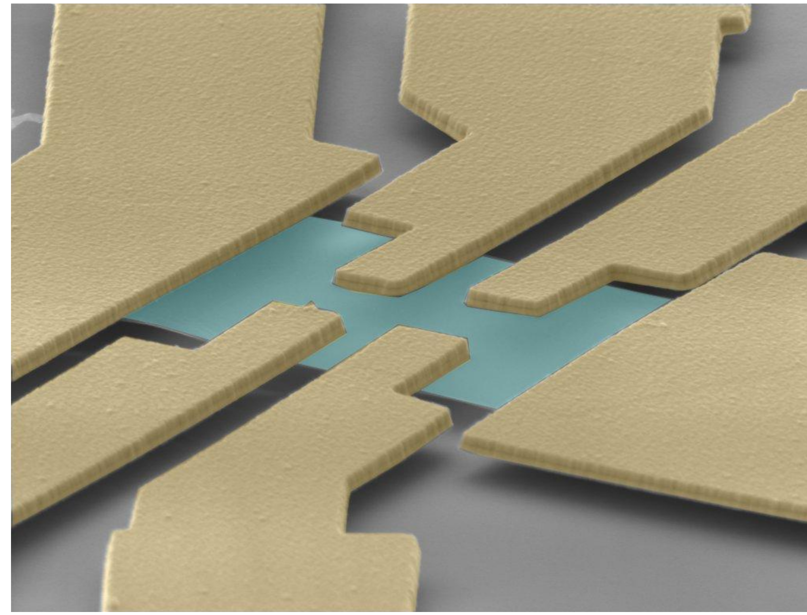
Developing SPM Measurements for Devices

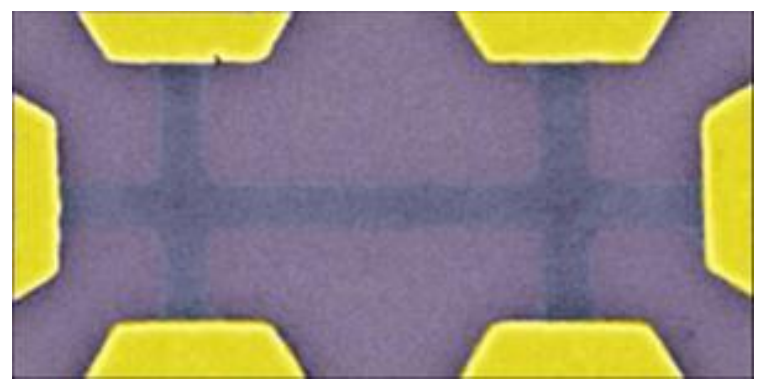
Graphene is Not Ideal in Real Devices





Y. Zhang et al. Nature (2010)

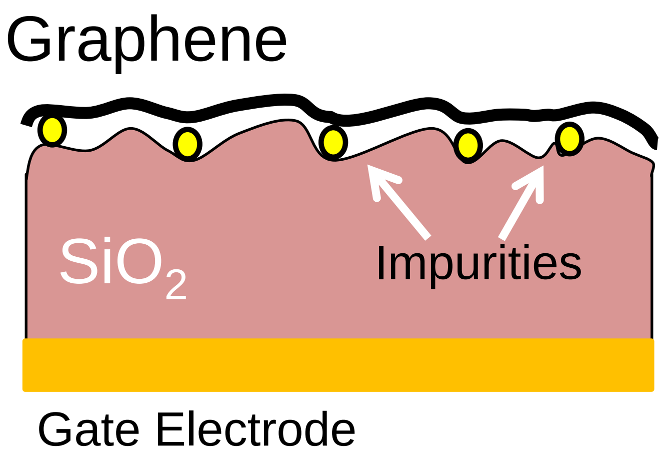


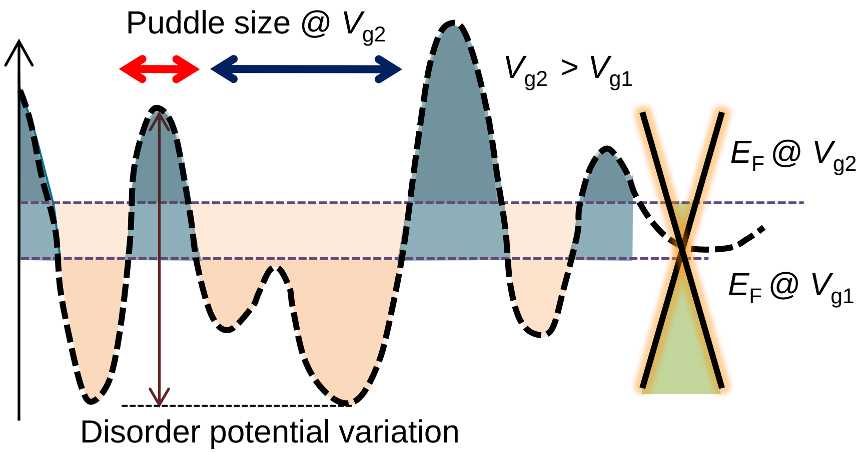


K. Novoselov et al. Nature (2005)

SPM Measurements in Graphene Devices

Potential Disorder in Graphene/SiO_2





How does disorder affect:

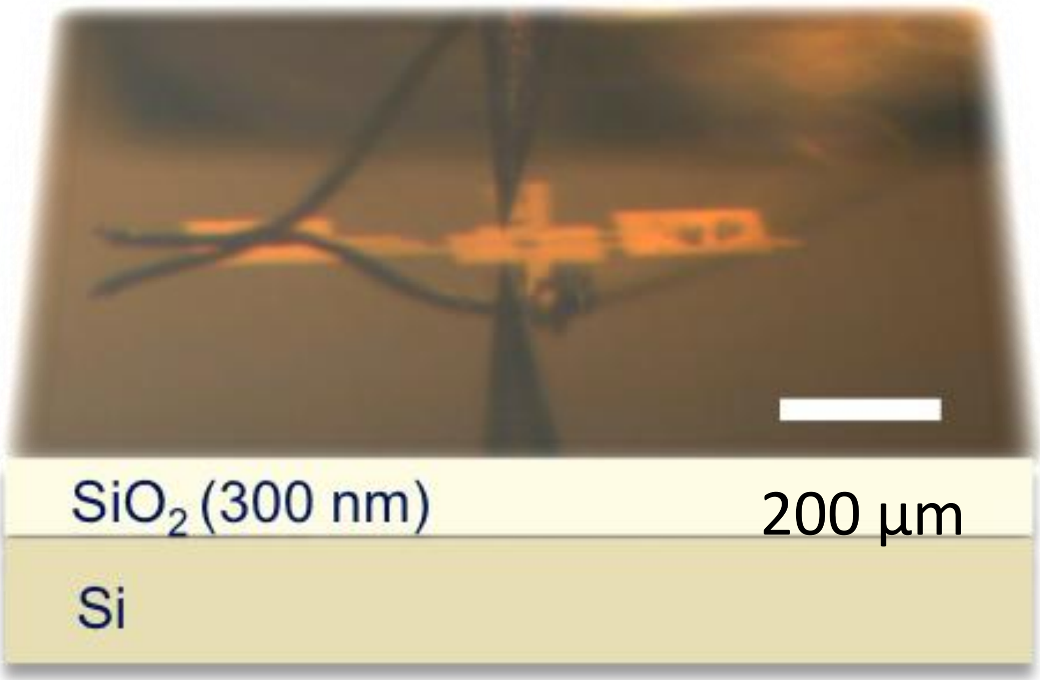
- Mobility
- Minimum conductivity
- Localization…

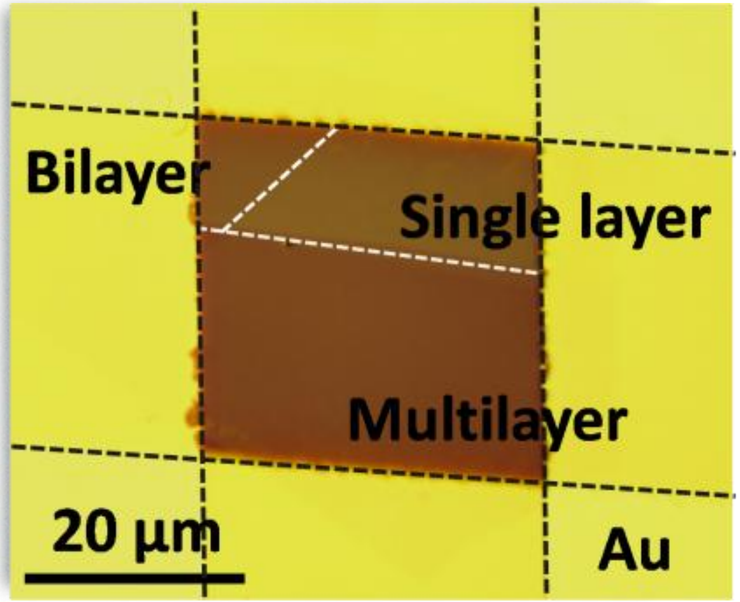
N. M. R. Peres et al. PRB (2006)
E. H. Hwang et al. PRL (2007)
J. Martin et al. Nature Phys. (2008), (2009)
E. Rossi and S. Das Sarma PRL (2009)
Y. Zhang et al. Nature Phys. (2009)
Etc……

SPM Measurements in Graphene Devices

Device Fabrication / Experimental Set-up

Optical viewing and probe alignment in CNST STM





- Mechanically exfoliated graphene on SiO_2/ Si substrate
- Single / bilayer confirmed by Raman spectroscopy
- Stencil mask evaporation

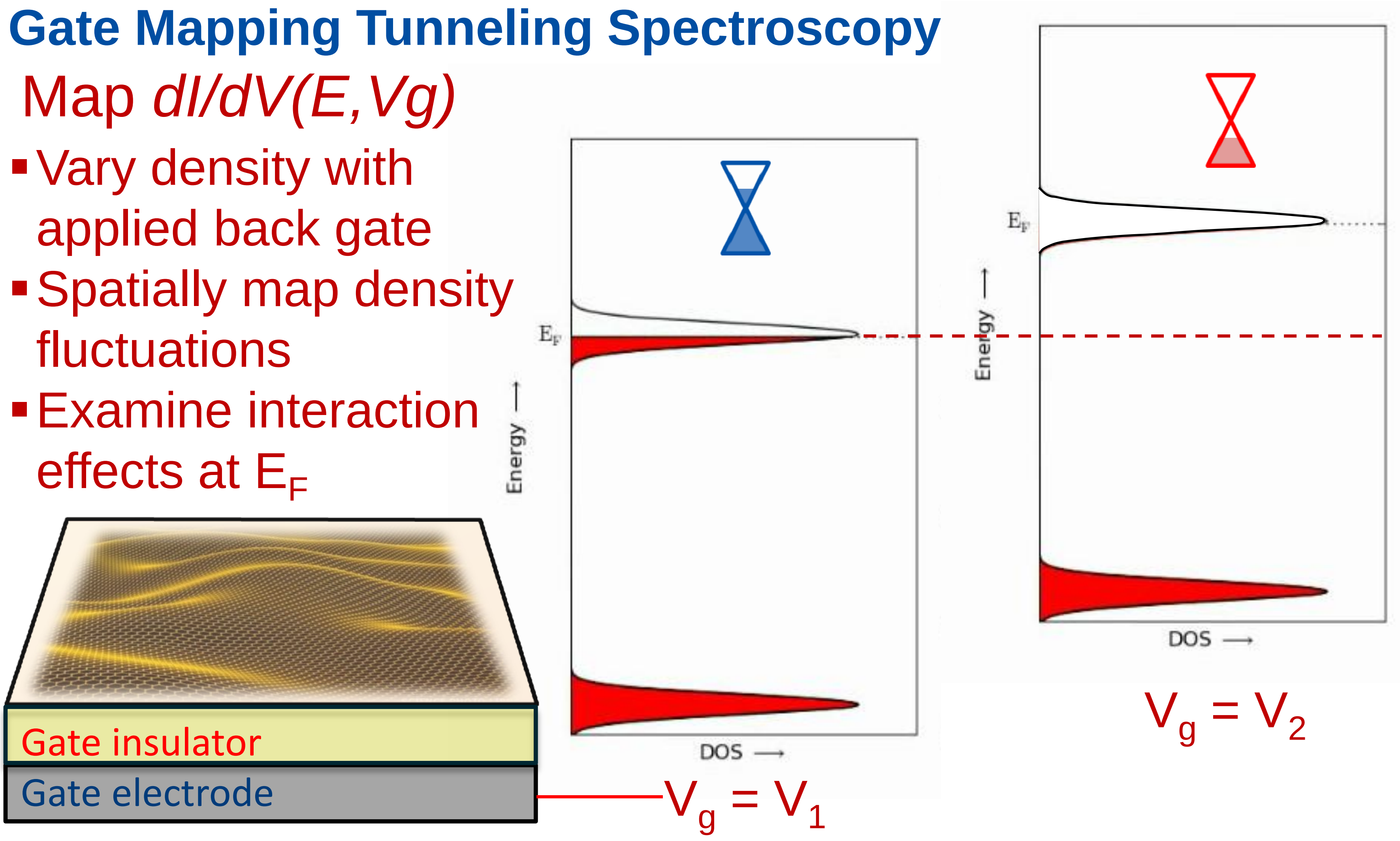
S. Jung et al. *Nature Physics* (2010)

LDOS vs Transport Measurements

Gate Mapping Tunneling Spectroscopy

Map *dI/dV(E,Vg)*

- Vary density with applied back gate
- Spatially map density fluctuations
- Examine interaction effects at E_F

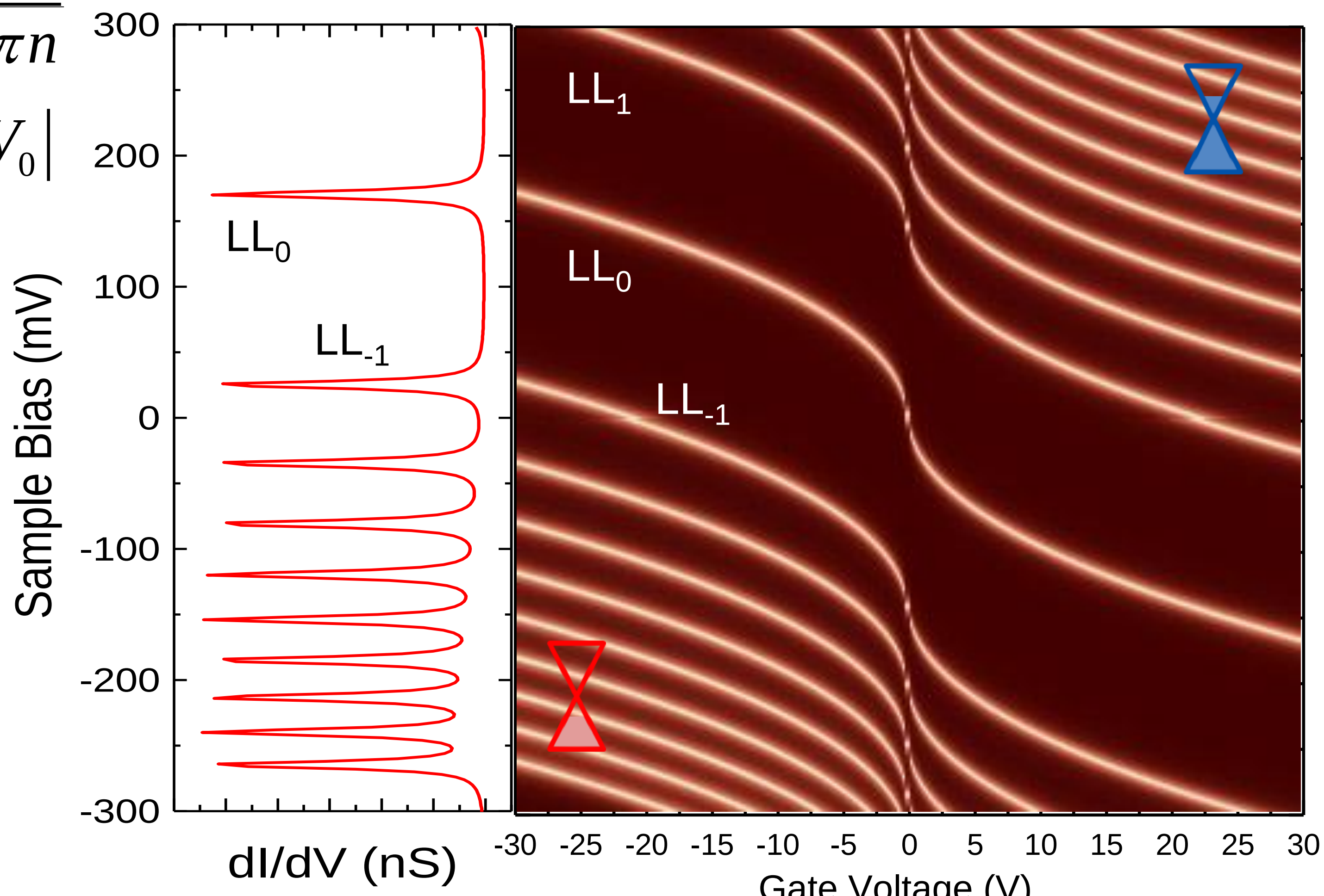


SPM Measurements of Graphene Devices

Gate Mapping Tunneling Spectroscopy (simulation)

$$E_D = \hbar v_F \sqrt{\pi n}$$

$$n = \alpha \left| V_G - V_0 \right|$$

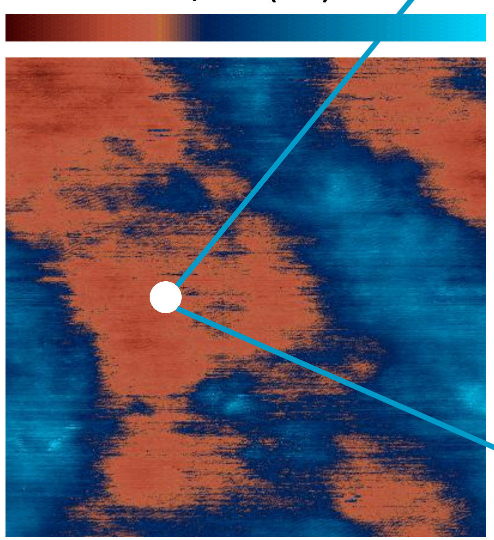


SPM Measurements of Graphene Devices

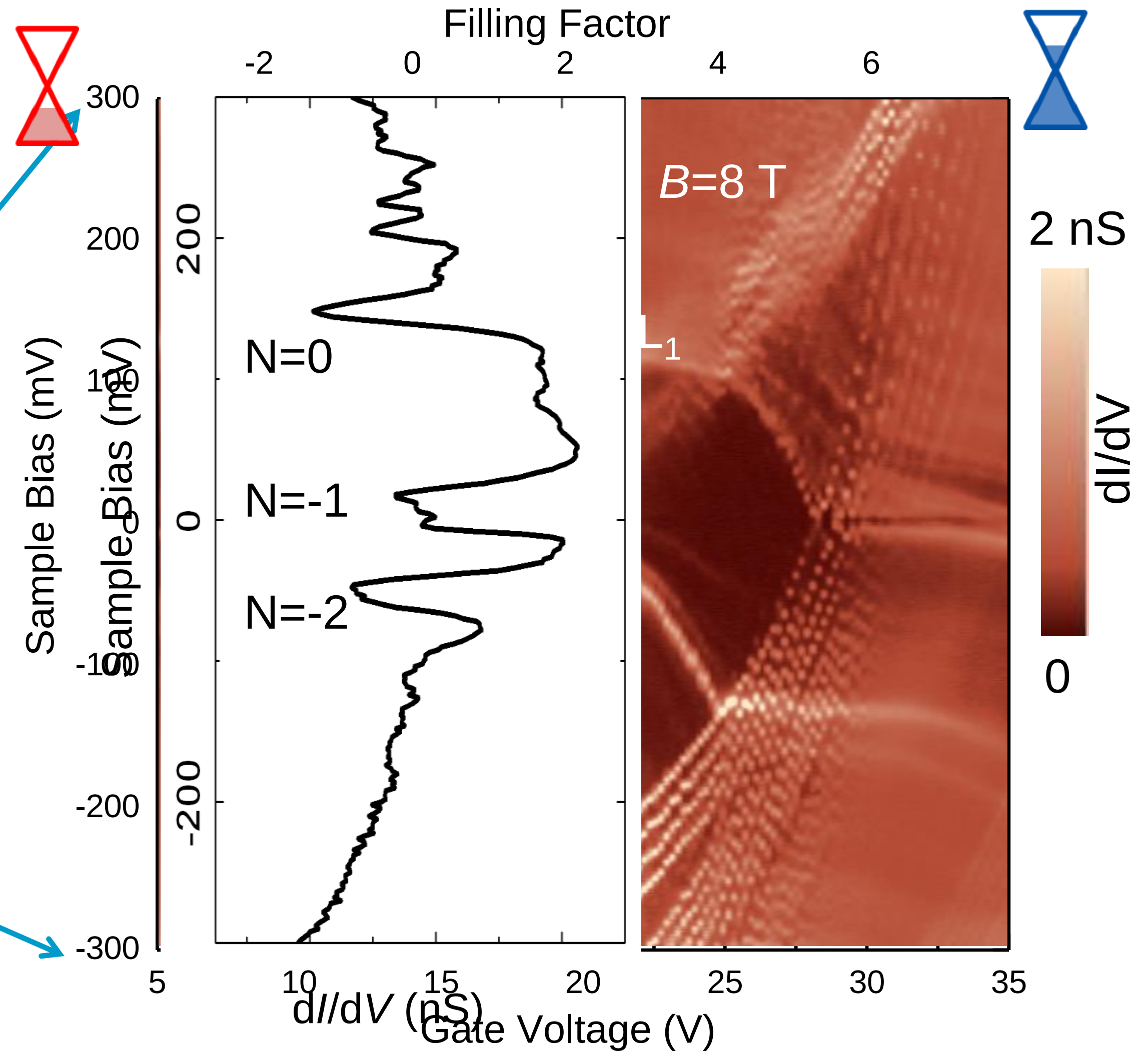
Gate Mapping Tunneling Spectroscopy in An Electron Puddle

S. Jung et al. *Nature Physics* (2010)

STS Measurement of Dirac Point Fluctuations

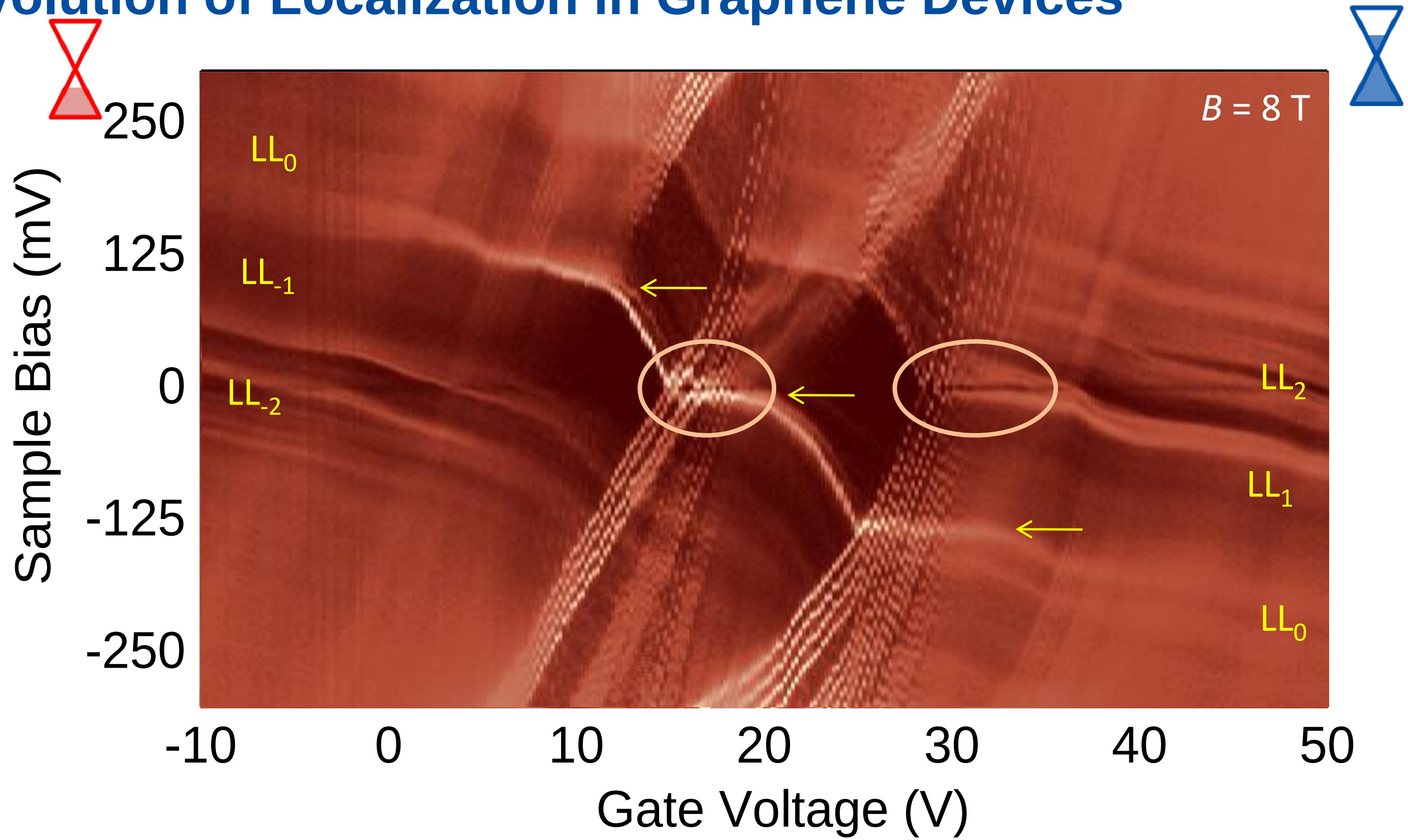


Potential Disorder Map



SPM Measurements of Graphene Devices

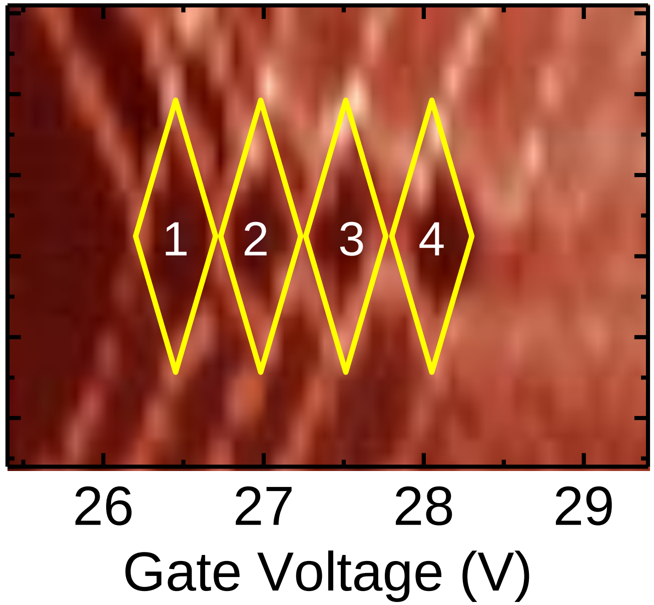
Evolution of Localization in Graphene Devices

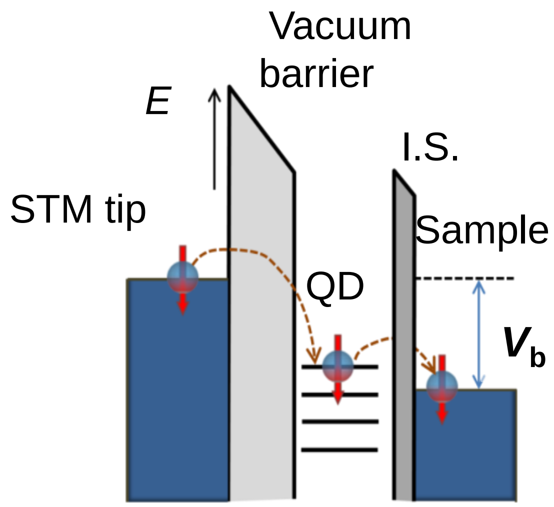


SPM Measurements of Graphene Devices

- **Graphene Quantum Dot Formation in High Field**
  - Coulomb blockade – Groups of four diamonds due to spin and valley degeneracy

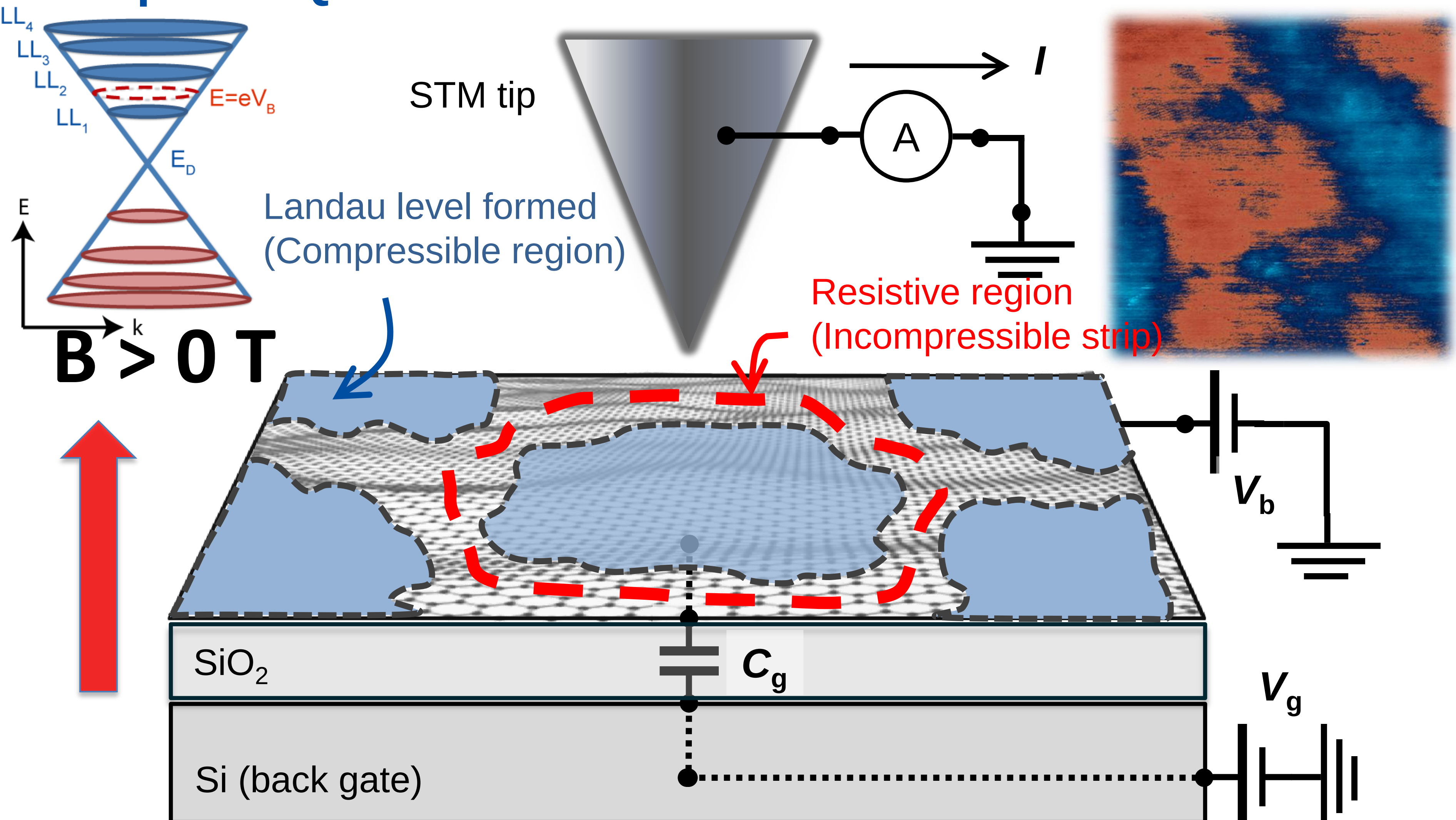
Double barrier tunneling due to vacuum barrier and incompressible regions





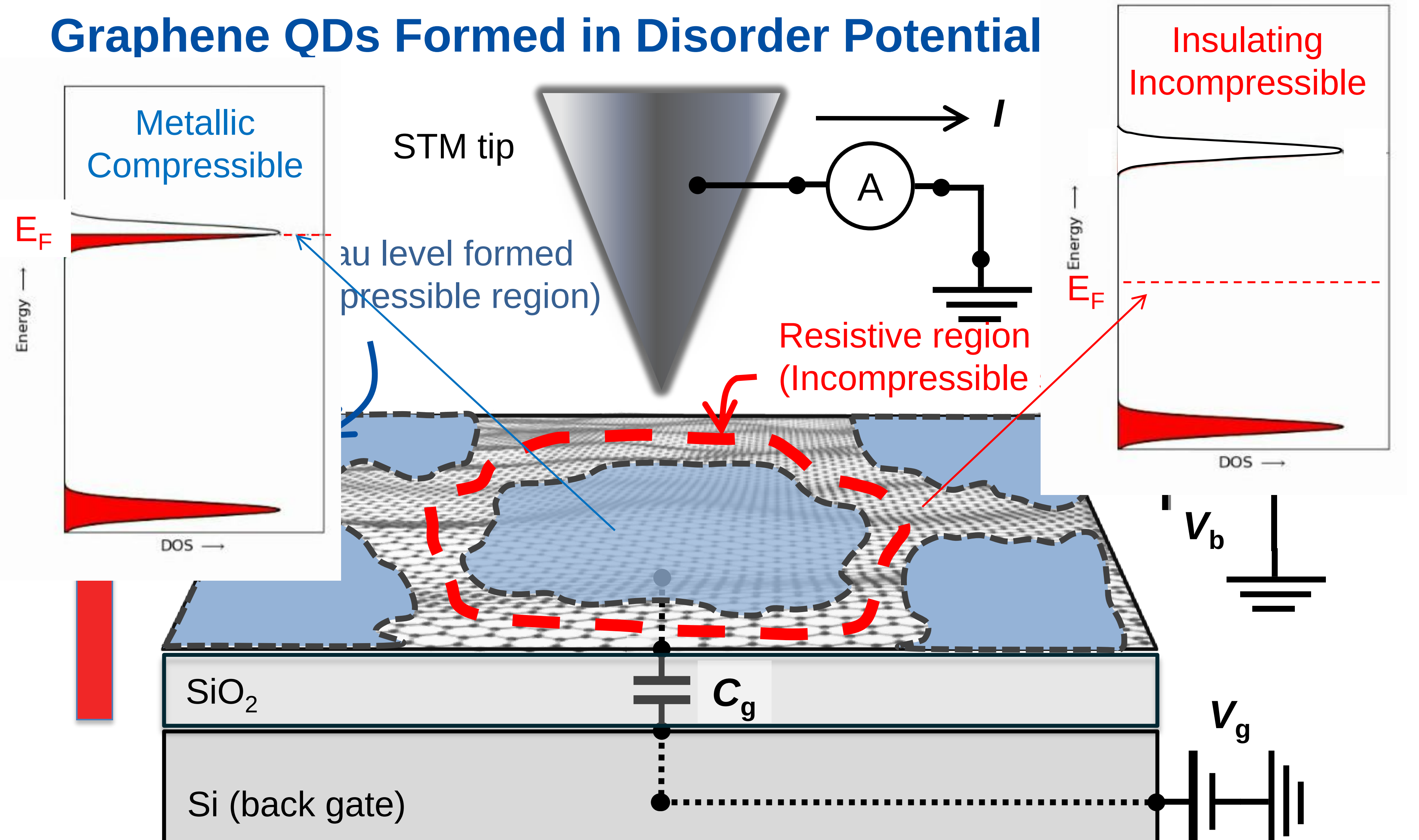
SPM Measurements of Graphene Devices

Graphene QDs Formed in Disorder Potential



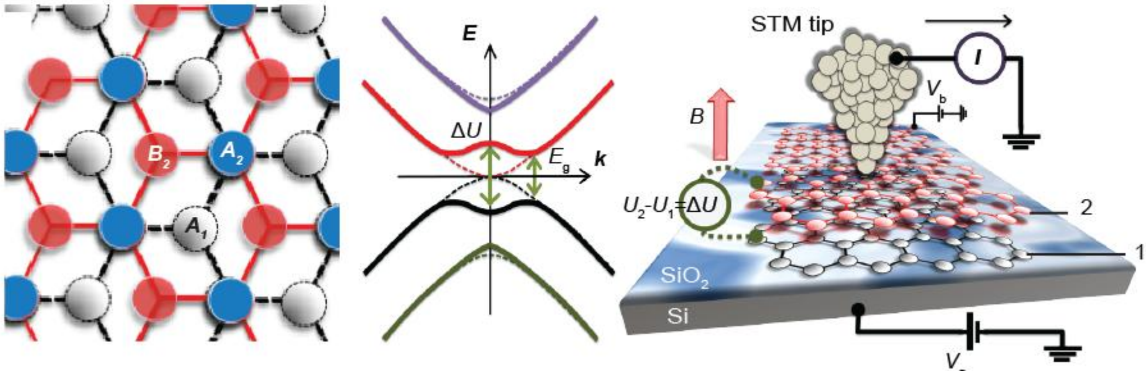
SPM Measurements of Graphene Devices

Graphene QDs Formed in Disorder Potential

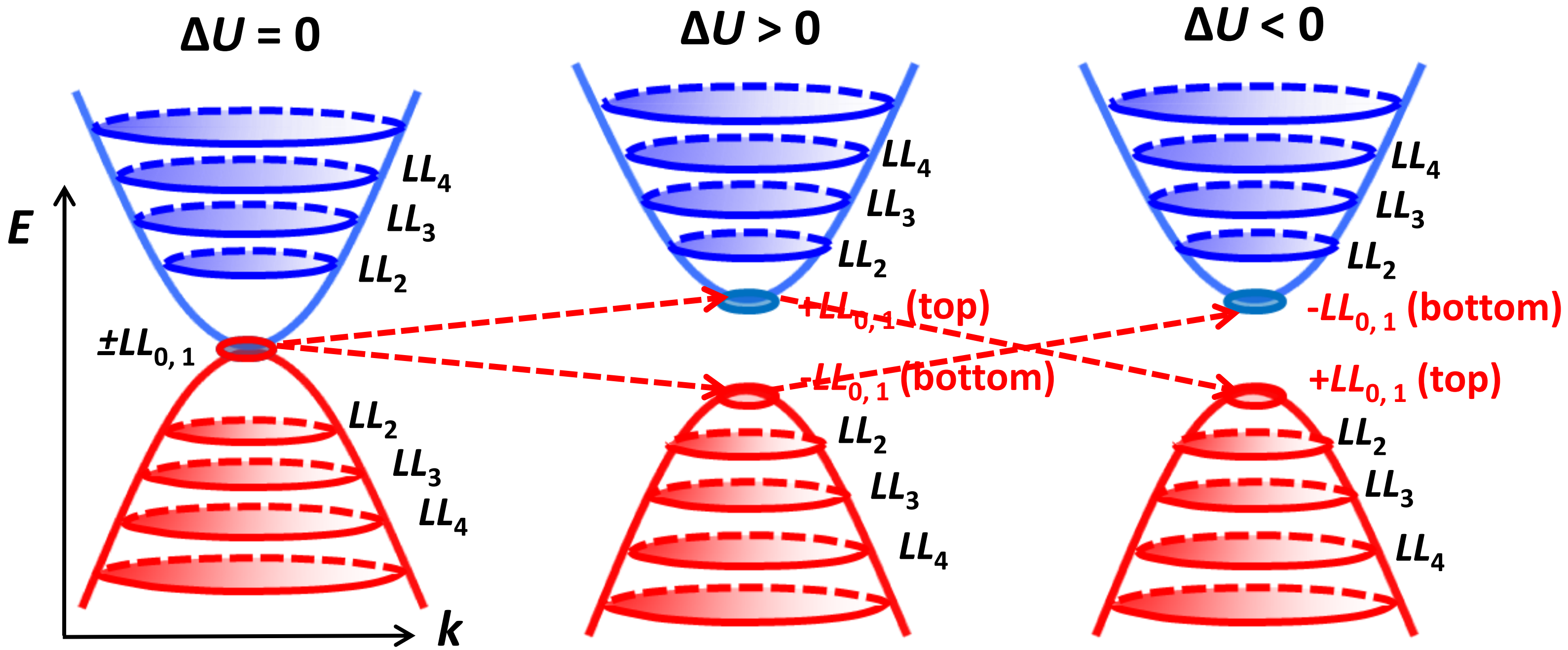


SPM Measurements of Bilayer Graphene Devices

STS Allows Direct Measurement of Bilayer Potentials

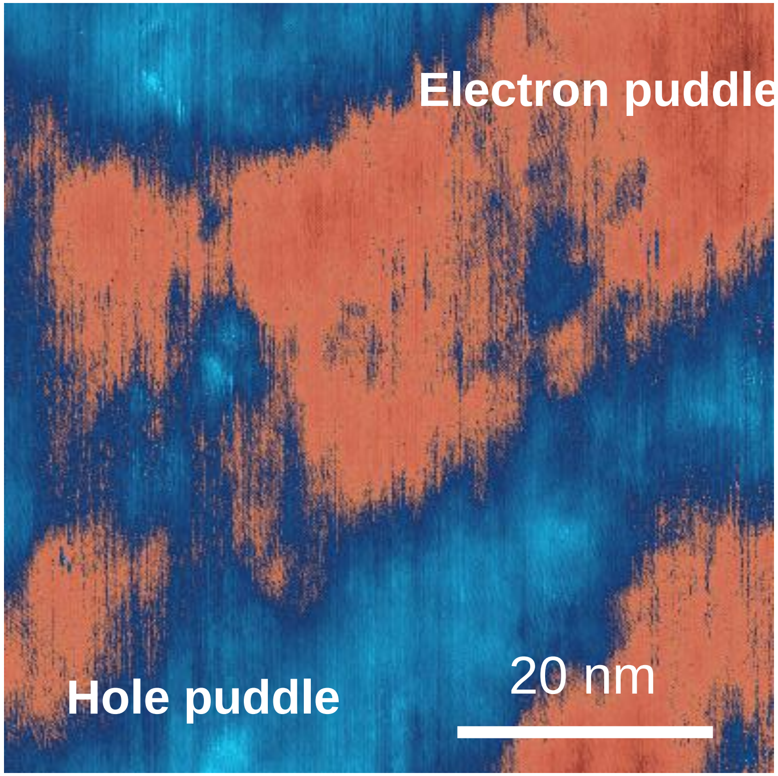


!STS Selects Layer Polarized States

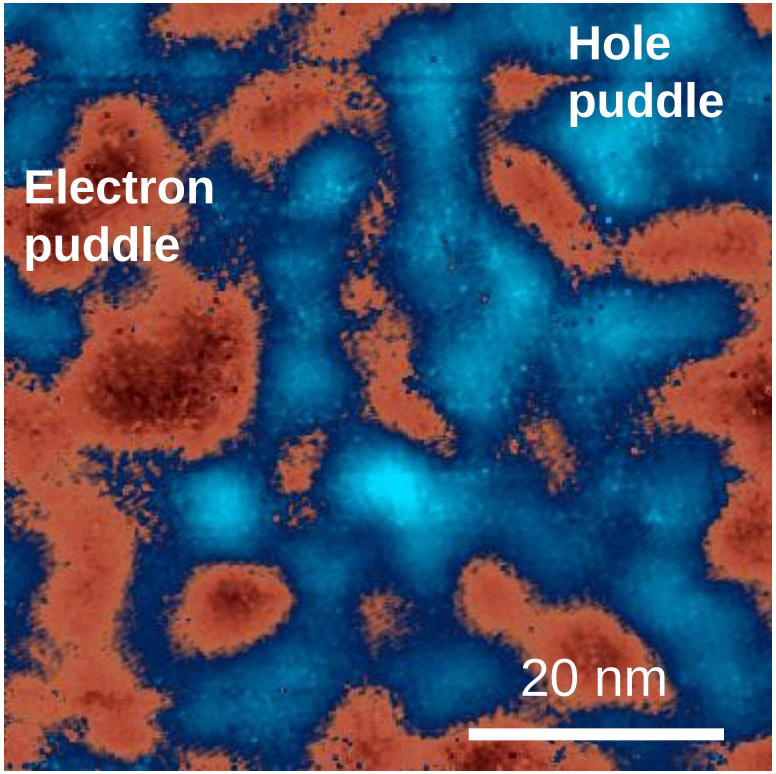


Probing Spatial Distribution of Disorder Potential

Single Layer

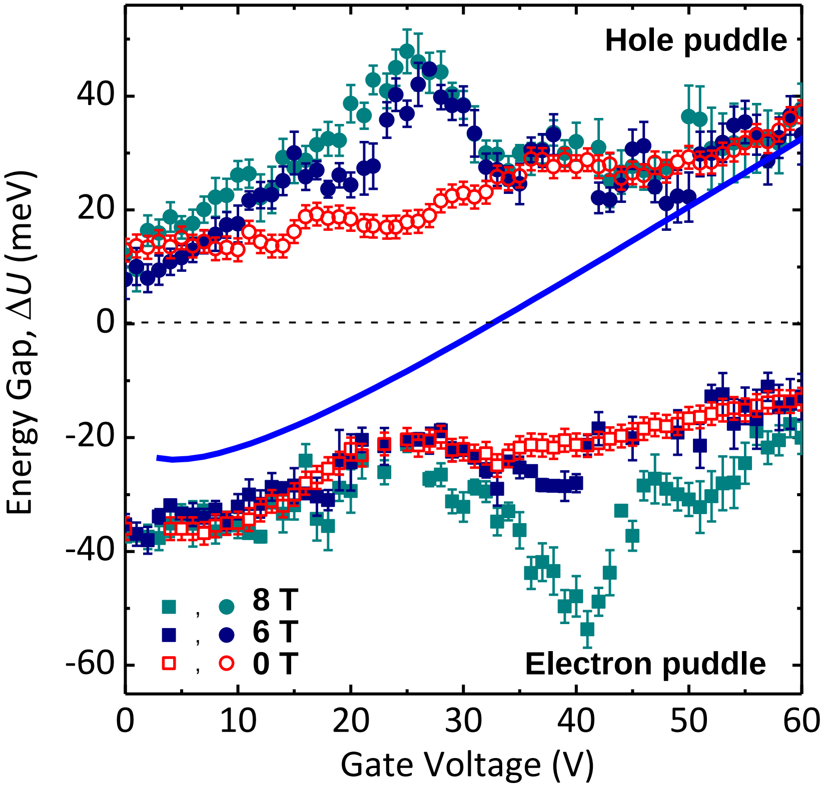


Bilayer

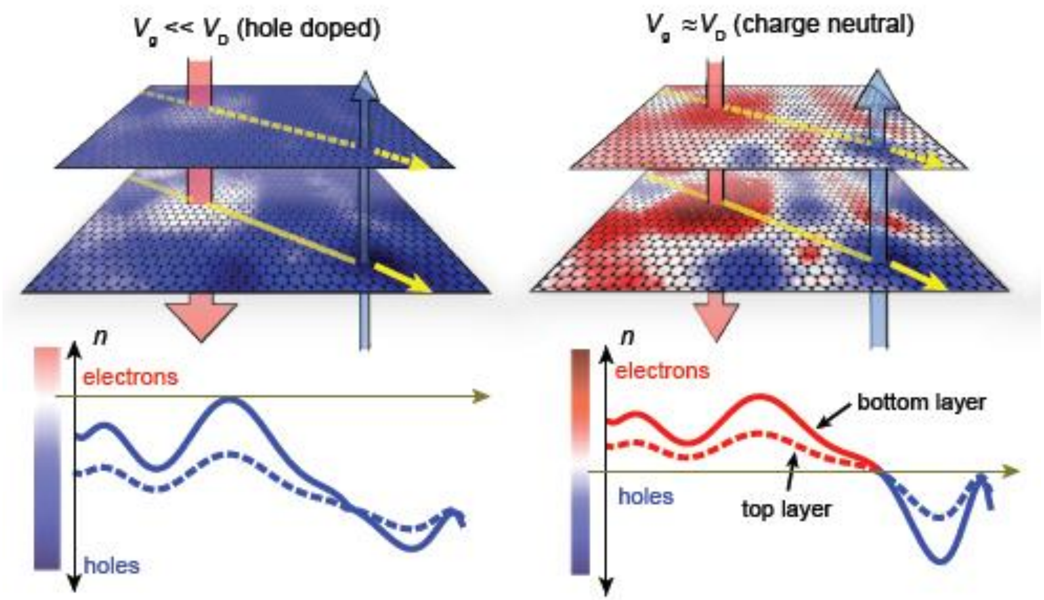


SPM Measurements of Bilayer Graphene Devices

Gate Mapping Allows Direct Measurement of Bilayer Gap



- Quantitative determination of bilayer gap
- Variation on a microscopic scale in both magnitude and sign



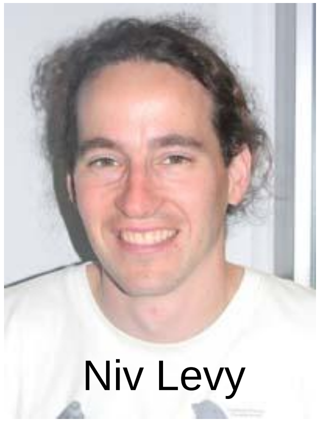
G. Rutter et al. *Nature Physics* (2011)

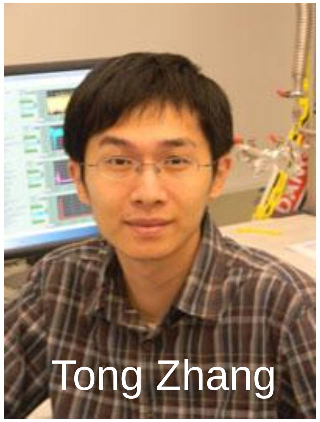
What's the Next in Atomic Scale Measurement Development

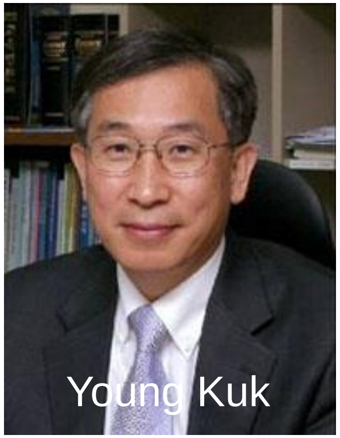
- Coordinated approach to combine new atomic-scale measurement methods, synthesis, and device fabrication
  - Atomic scale and macroscale measurements on the same test devices
    - How does microscale properties from substrates/gate insulators, contacts etc… determine macroscale performance
    - Develop measurements for new qraphene device concepts, *i.e*. Veslago lens BiSFET device
  - Fabrication and measurement of topological insulators – more Dirac
    - MBE and bulk crystal growth, atomic characterization studies
  - Combined STM, AFM and spin-polarized STM on device geometries
    - New high-throughput STM/AFM/SGM system
  - Multi-terminal STM/STS measurements on devices that combine simultaneous transport and atomic characterization measurements to optimize device performance
  - Continue to seek collaborations that leverage our capabilities

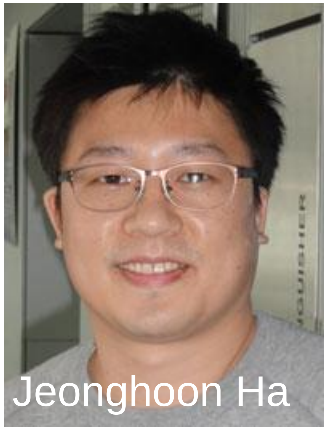
Collaborators

Graphene/TI mK Crew



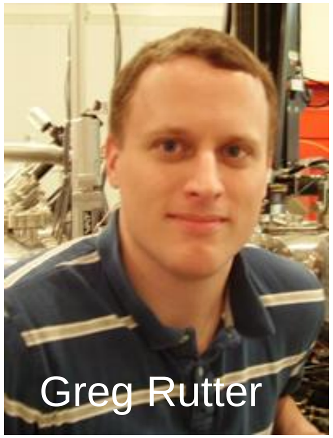






Collaborators

Graphene Device Crew

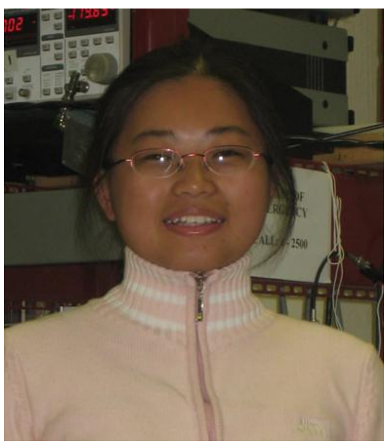


Collaborators

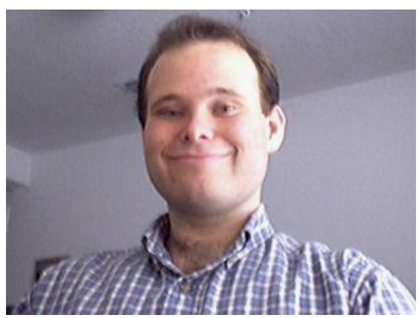
GT Epitaxial Graphene Crew

Phil First

Walt de Heer

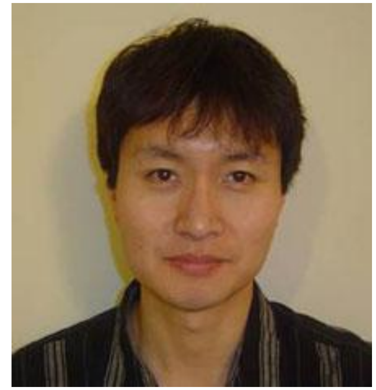


Yike Hu



Britt Torrance

Graphene Theory Crew

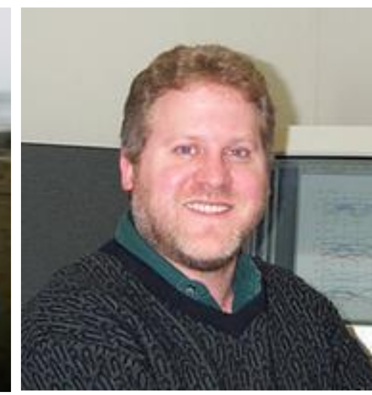


Hongki Min

Shaffique Adam

Mark Stiles

Allan MacDonald



Eric Cockayne