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

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Presentation Outline

Microscopy

Honeycomb Lattices

Magnetic Fields

Graphene Devices

Graphene “Quartet”

Low temperature

NIST Center for Nanoscale Science & Technology
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”

http://www.eatechnology.com

18th century microscopes
Musée des Arts et Métiers, Paris

Wikipedia
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 Ernst Ruska (electron microscope)

\[ I \propto e^{-2\kappa d} \]

from Wikipedia
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”

\[ I \propto \int_{E_F}^{E_{F+V}} \rho(r_t, E) \, T(E, V) \, dE \]

\[ \rho(r_t, E) = \sum_v \left| \psi_v(r_t) \right|^2 \delta(E_v - E) \]

\[ \frac{dl}{dV} \propto \rho(r_t, E) , B , V_g \]


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 $\sim 3k_B T$
- Solution: Go to lower temperatures
  - Not so easy!

$T = 295 \text{ K}$
$T = 4 \text{ K}$
$T = 0.6 \text{ K}$
$T = 10 \text{ mK}$

1981
1990
2004
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

ULTSPM Lab at NIST

Processing Lab

Vibration Isolation

Stage 3

Stage 2

Stage 1
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

Graphene/SiC

T = 13 mK

Y. J. Song et al. RSI (2010)
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B
From Honeycombs to the Dirac Hamiltonian

Graphene – Light-like Electrons
From Pencil Drawings to High Speed Transistors to iPad? Or Galaxy Tab?


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 Basics

Carbon with 4 valence electrons

Two atom basis in the unit cell → pseudo-spin

Top View (real space)
Energy is linear with momentum massless particles
Low Energy Expansion: Dirac Hamiltonian

Real space:

For behavior away from Dirac point, make an expansion:

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

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

Reciprocal space:

\[ H_K = v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} = v_F \sigma \cdot k \]

\[ E = \pm v_F k \quad \psi_{\pm,K}(k) = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{-i\theta_k/2} \\ \pm e^{-i\theta_k/2} \end{pmatrix} \]

\[ \theta_k = \arctan \left( \frac{k_x}{k_y} \right) \]

Paul Dirac
The Independent Two Valleys

\[ H_K = \nu_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} \]

Leads to additional degeneracy

\[ H_{K'} = \nu_F \begin{pmatrix} 0 & k_x + ik_y \\ k_x - ik_y & 0 \end{pmatrix} \]
Consequences of Dirac Hamiltonian

Pseudo-spin; reduced backscattering

Klein tunneling; transmission through potential barriers

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Graphene “Quartet”
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

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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

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

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NIST Center for Nanoscale Science & Technology
Epitaxial Graphene on C-face SiC – Weak Disorder

Induction Furnace Method

C-Face termination

\( (000\bar{1}) \)

SiC

\( (0001) \)

Si-Face termination

Graphene layers

J. Hass et al., PRL 100, 1255504 (2008)
Berger et al., Science 312, 1191 (2006)
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

Resolving the Graphene Quartet

Tunneling Spectroscopy at \(\sim 10 \text{ mK}\)

Graphene on C-face SiC


Zero field Dirac point is at \(-125 \text{ meV}\) indicating a doping of \(\sim 1 \times 10^{12} \text{ cm}^{-2}\)
Resolving the Graphene Quartet

Tunneling Spectroscopy at \( \sim 10 \text{ mK} \)

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

\[ \Delta V_{\text{rms}} = 1 \text{ mV} \]

\[ \Delta V_{\text{rms}} = 50 \mu\text{V} \]

Resolving the Graphene Quartet

Tunneling Spectroscopy at \( \sim 10 \) mK

Smaller peak separation – electron spin?

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

\[ g_s = 2.26 \pm 0.05 \]

\( \Delta V_{\text{rms}} = 50 \, \text{μV} \)

Resolving the Graphene Quartet

Tunneling Spectroscopy at \( \sim 10 \text{ mK} \)

Valley splitting is ten times larger than smaller energy splitting

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

\[
\Delta V_{\text{rms}} = 50 \text{ \mu V}
\]

Many Body Effects in Graphene

Polarizing Landau Levels

Filling factor = 6

Sample Bias (mV)

Fermi Level
Many Body Effects in Graphene

Polarizing Landau Levels

Filling factor = 5

Enhanced spin splitting at odd filling factors
Enhanced valley splitting at \( v = 4 \)
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

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

Tsuneys Ando and Yasutada Uemura
Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113
(Received May 14, 1974)
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Graphene “Quartet”
Developing SPM Measurements for Devices

Graphene is Not Ideal in Real Devices


SPM Measurements in Graphene Devices

Potential Disorder in Graphene/SiO$_2$

Graphene

SiO$_2$

Impurities

Gate Electrode

How does disorder affect:
• Mobility
• Minimum conductivity
• Localization...

N. M. R. Peres et al. PRB (2006)
E. H. Hwang et al. PRL (2007)
E. Rossi and S. Das Sarma PRL (2009)
Etc...
SPM Measurements in Graphene Devices

Device Fabrication / Experimental Set-up

- Mechanically exfoliated graphene on SiO$_2$/ Si substrate
- Single / bilayer confirmed by Raman spectroscopy
- Stencil mask evaporation


Optical viewing and probe alignment in CNST STM

![Image of graphene device]
LDOS vs Transport Measurements

Gate Mapping Tunneling Spectroscopy

Map $dl/dV(E, V_g)$
- Vary density with applied back gate
- Spatially map density fluctuations
- Examine interaction effects at $E_F$

Gate insulator

Gate electrode

$V_g = V_1$

$V_g = V_2$
SPM Measurements of Graphene Devices

Gate Mapping Tunneling Spectroscopy (simulation)

\[ E_D = \hbar v_F \sqrt{\pi n} \]
\[ n = \alpha |V_G - V_0| \]

![Graphene Device Spectroscopy Simulation](image_url)
SPM Measurements of Graphene Devices

Gate Mapping Tunneling Spectroscopy in An Electron Puddle


STS Measurement of Dirac Point Fluctuations

Potential Disorder Map

Sample Bias (mV)

Gate Voltage (V)

Sample Bias (mV)

Gate Voltage (V)

Filling Factor

STS Measurement of Dirac Point Fluctuations


Potential Disorder Map

Sample Bias (mV)

Gate Voltage (V)

Filling Factor

STS Measurement of Dirac Point Fluctuations

SPM Measurements of Graphene Devices

Evolution of Localization in Graphene Devices

Sample Bias (mV) vs. Gate Voltage (V)

-250 -125 0 125 250
-10 0 10 20 30 40 50

$B = 8 \text{T}$

LL$_0$, LL$_1$, LL$_2$
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

26 27 28 29
Gate Voltage (V)
SPM Measurements of Graphene Devices

Graphene QDs Formed in Disorder Potential

$E = eV_b$

Landau level formed (Compressible region)

Resistive region (Incompressible strip)

$V_b$

$V_g$

$C_g$

$\text{SiO}_2$

$\text{Si (back gate)}$

$B > 0 \ T$

STM tip
SPM Measurements of Graphene Devices

Graphene QDs Formed in Disorder Potential

Metallic Compressible

STM tip

Resistive region (Incompressible)

Insulating Incompressible

\( E_F \)

\( V_b \)

\( V_g \)

\( C_g \)

SiO\(_2\)

Si (back gate)
SPM Measurements of Bilayer Graphene Devices

STS Allows Direct Measurement of Bilayer Potentials

\[ \Delta U = 0 \]

\[ \Delta U > 0 \]

\[ \Delta U < 0 \]

STS Selects Layer Polarized States
Probing Spatial Distribution of Disorder Potential

Single Layer

Electron puddle

Hole puddle

20 nm

Bilayer

Electron puddle

Hole puddle

20 nm
Gate Mapping Allows Direct Measurement of Bilayer Gap

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

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 graphene 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

Young Jae Song  Sander Otte  Niv Levy  Tong Zhang

Young Kuk  Jungseok Chae  Jeonghoon Ha
Collaborators

Graphene Device Crew

- Greg Rutter
- Suyong Jung
- Nikolai Klimov
- Nikolai Zhitenev
- Dave Newell
- Angie Hight-Walker
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