Quantum Electrodynamics in Graphene

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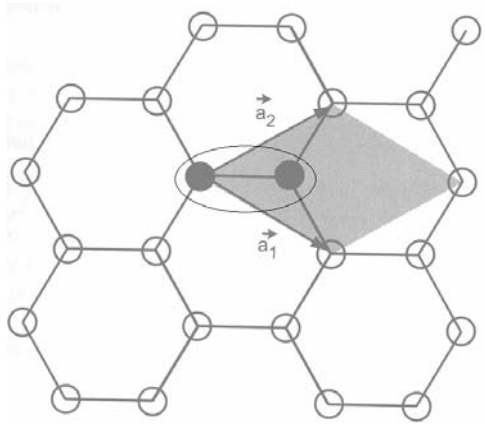
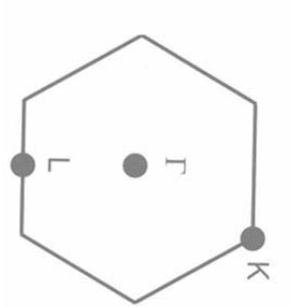
Graphene

- Single layer of Graphite- 2D crystal
- Honeycomb lattice
- Interlayer distance 0.35 nm
- Hexagonal Brillouin Zone (BZ).
- 2 atom per unit cell
- sp^2 hybridized.
- 2 free electron / unit cell

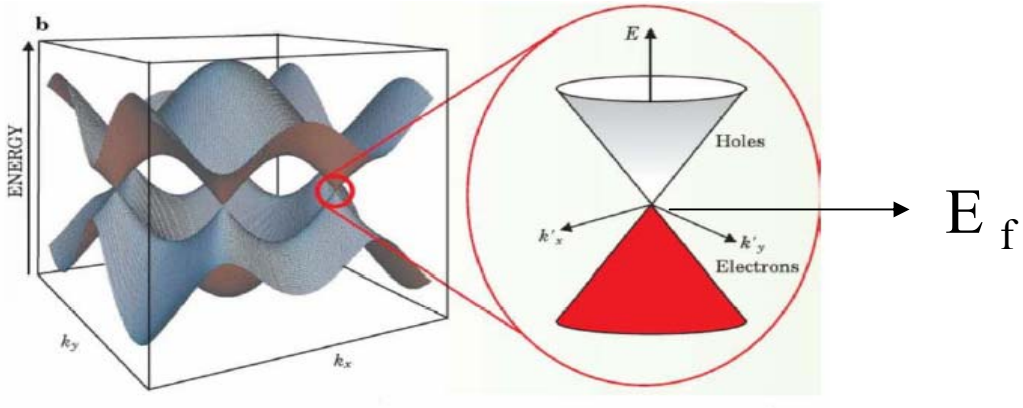


Real space



Brillouin Zone

Massless Dirac Fermions



- Valence Band & Conduction band touches at corners of BZ.
- Two inequivalent points K and K'. Dirac points(DP)
- Energy relation is linear $\varepsilon = \frac{|h\,\mathbf{k}|}{2\pi} v_f$ in the vicinity of DP
- Electron dynamics obey 2D Relativistic Dirac Equation.

Consequences of Dirac Dispersion Curve

- Zero effective mass
- Charge carriers are Massless Relativistic Dirac Fermions
- In B-field , Landau Level (LL) spectrum is different from that exhibited by ordinary metals
- Results in Unconventional Quantum hall Effect (QHE)

Discovery

- *Two Dimensional Gas of Massless Dirac Fermions in Graphene, Nature Vol 438* 2005 ,

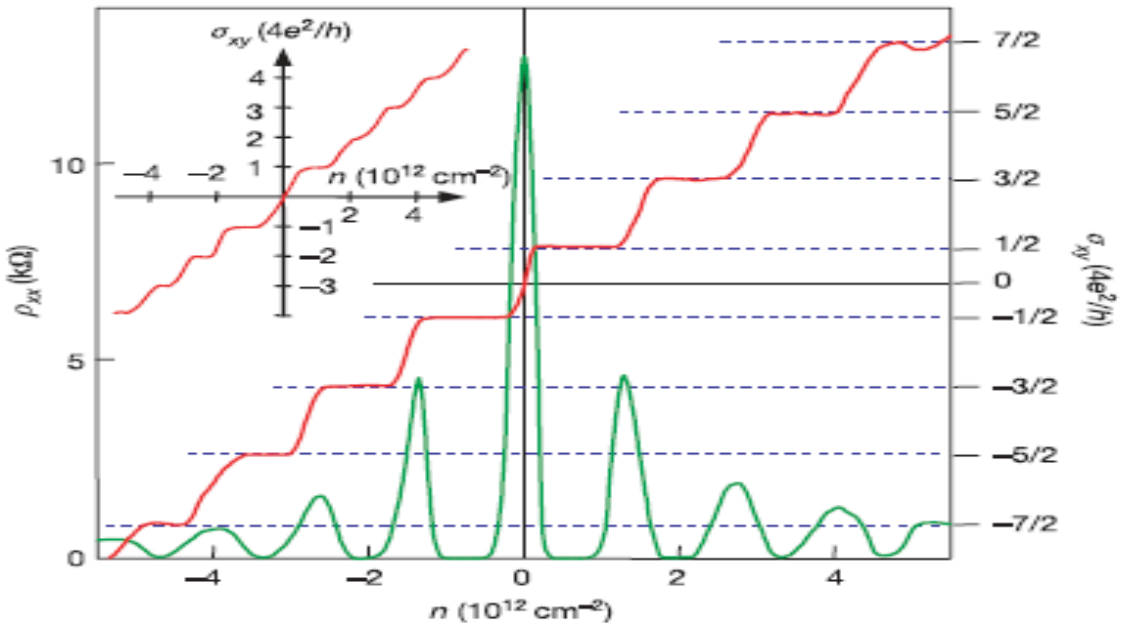
  K.S. Novoselov et.al Univ. of Manchester UK.

- *Experimental Observation of the quantum hall effect and Berry's phase in graphene Nature 438, Nov 2005*

  Philip Kim et. al Columbia University

Unconventional Quantum Hall Effect

- Hall conductivity $\sigma_{xy} = \frac{4e^2}{h}\left(N + 1/2\right)$
- Plateaus occur at half –integer filling factors



Nature vol 438,10 Nov 2005 , Two dimensional gas of massless Dirac Fermions

Other Results

- Conductivity never falls below a particular value at Dirac points. $\rho_{\max} = h / fe^2$
- Shubnikov de Haas Oscillations show phase shift (Berry's Phase) of π
- Due to extra Half in Hall conductivity.
- Bi-layer exhibit different properties.

Goals of our Project

- Reproduce graphene
- Try to find a better way of deposition and identification
- Confirm the electrical measurements.
- Prepare ground for experiments on
  - ❖ QED(Klein Paradox)
  - ❖ Adsorbing alkaline dopants (Na, Ag)
  - ❖ 2D superconductor

Techniques

- Tried different methods.
  - Plain Rubbing
  - Rubbing using two chips
  - Deposition Under Liquids.
  - Heating Wafer
  - Rubbing followed by sonication
  - Plain rubbing followed by transfer

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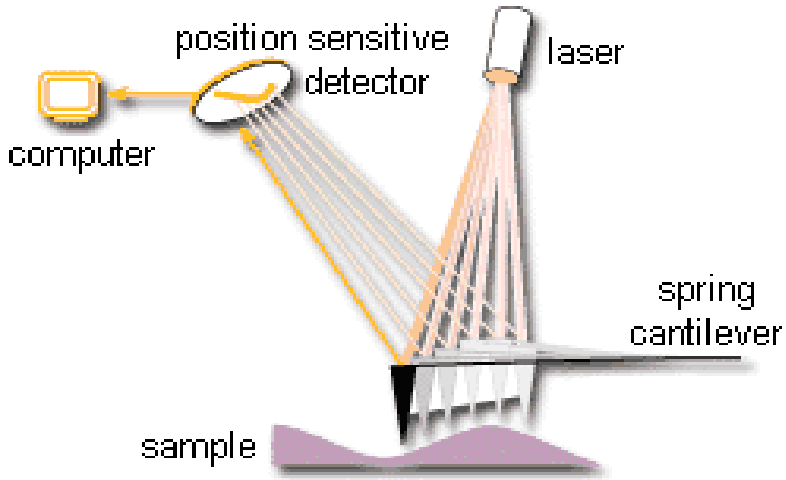
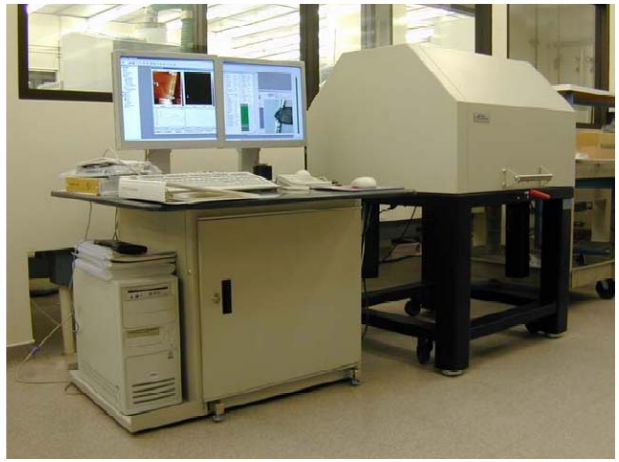
Preliminary Analysis using Optical Microscope

- Meiji Optical Microscope
- Scan through the Chip
- Identify possible candidates
- Take *snap shots*

Analysis by Atomic Force Microscope





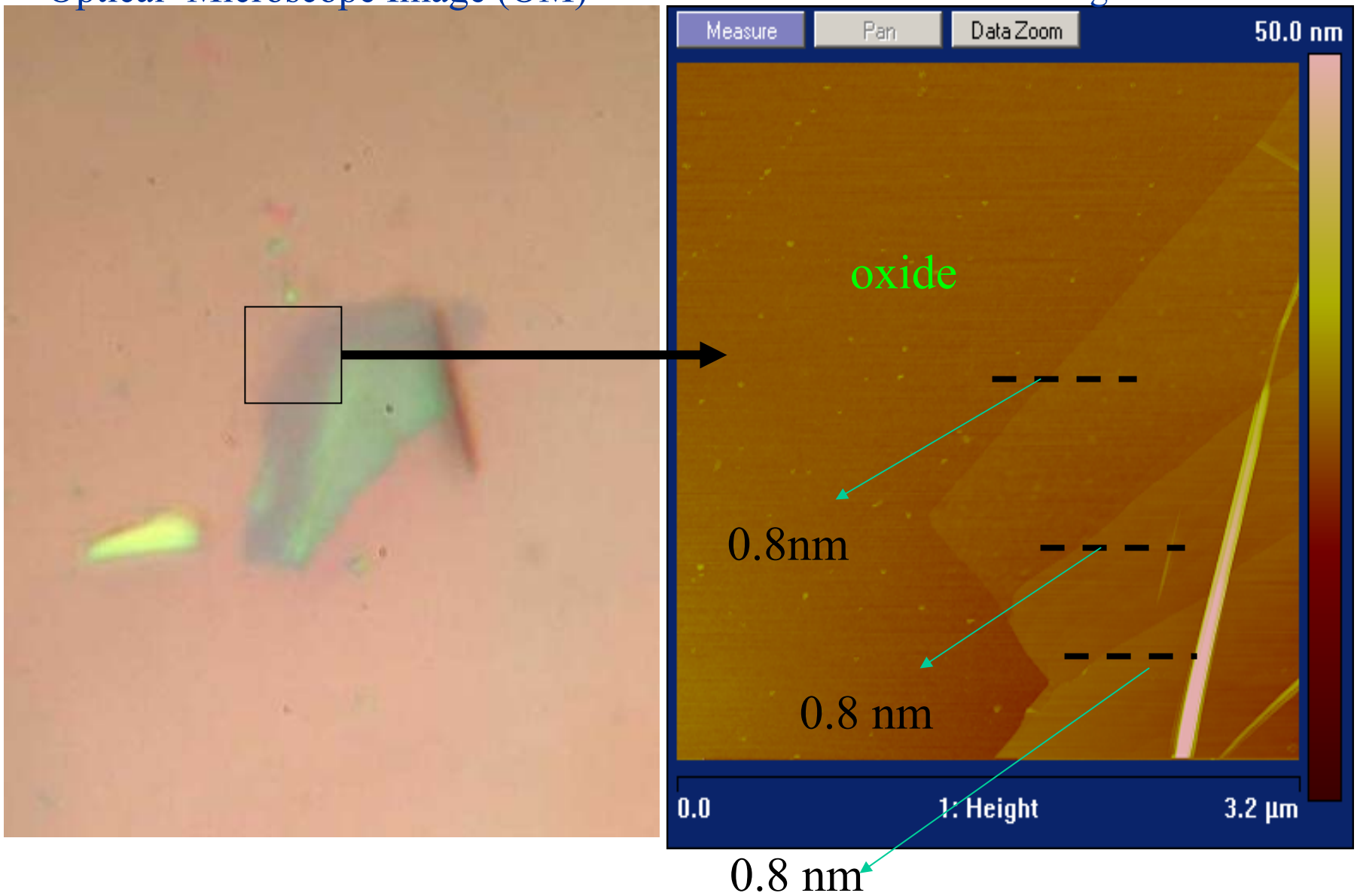
Dimension 3100 AFM.

- Tapping Mode – Cantilever taps on the sample

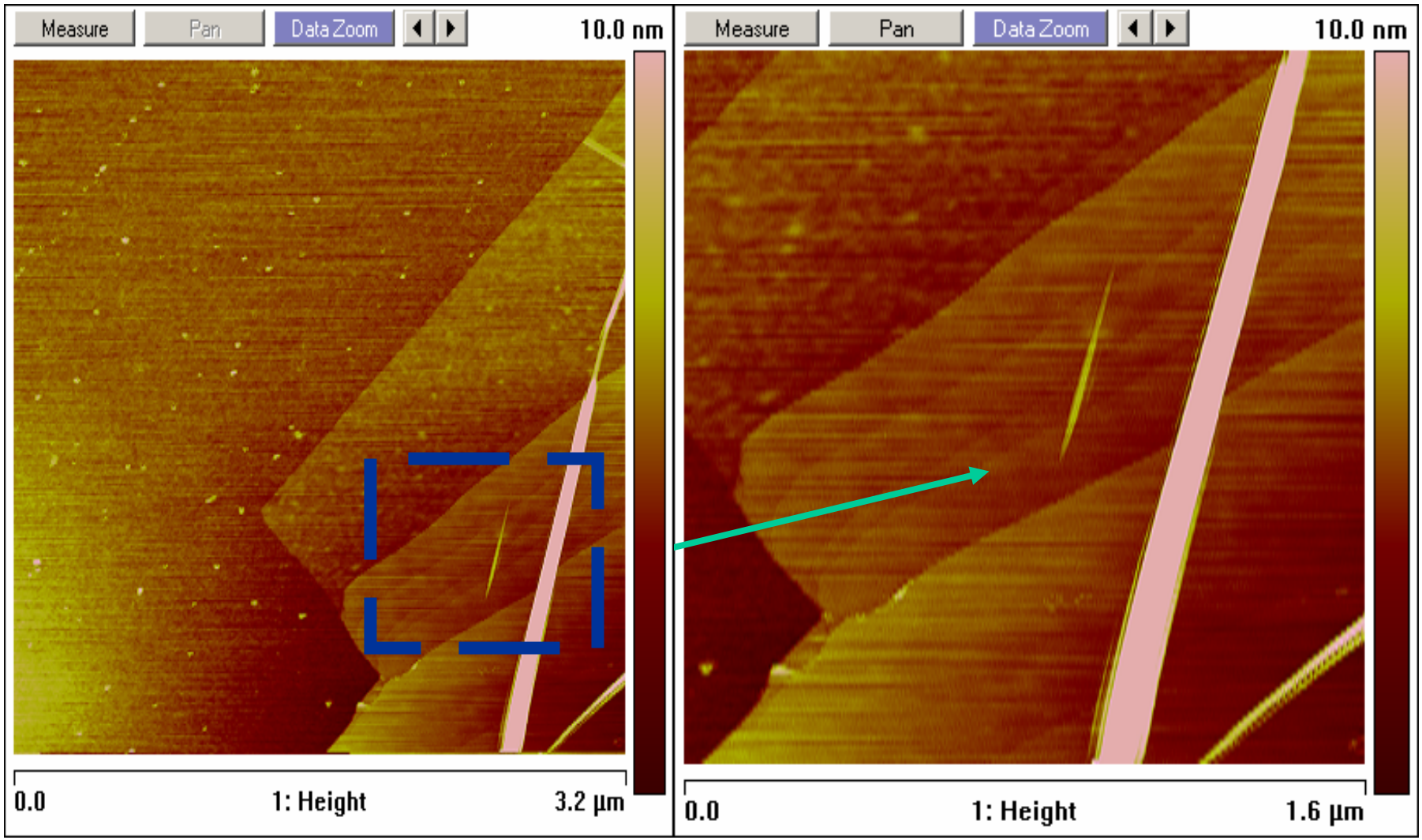
Sample # 1

Optical Microscope Image (OM)

AFM Image

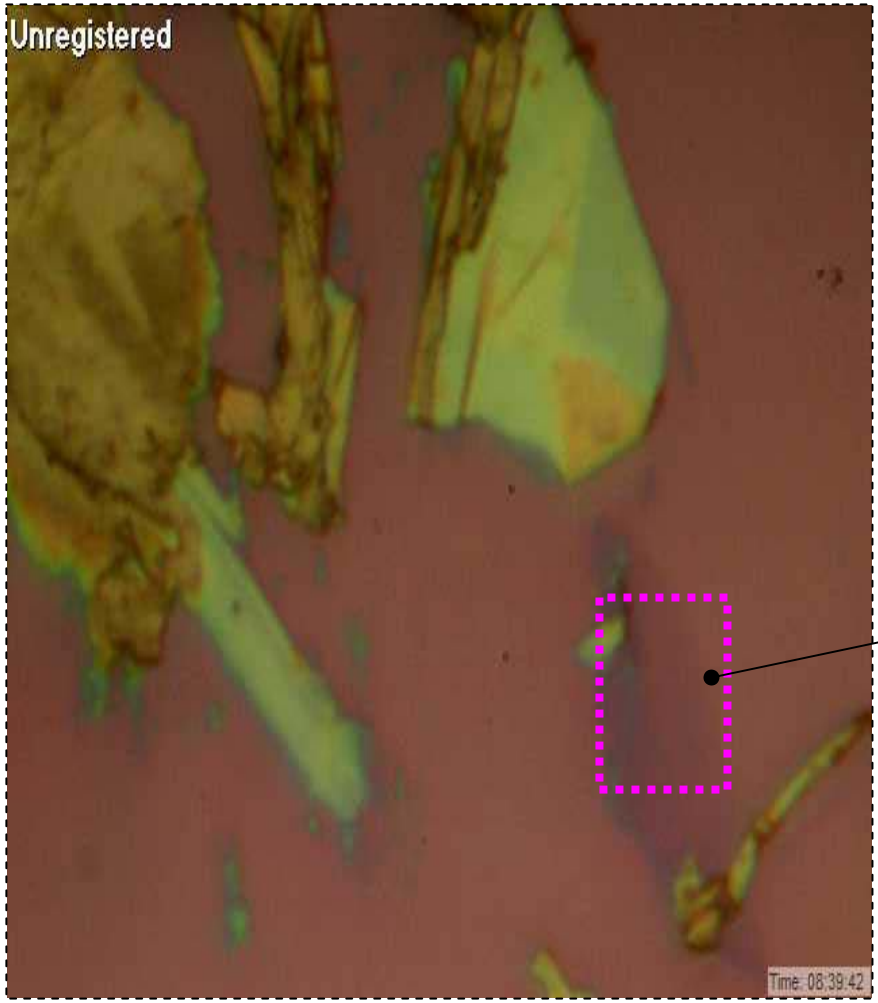


Folding of Layers

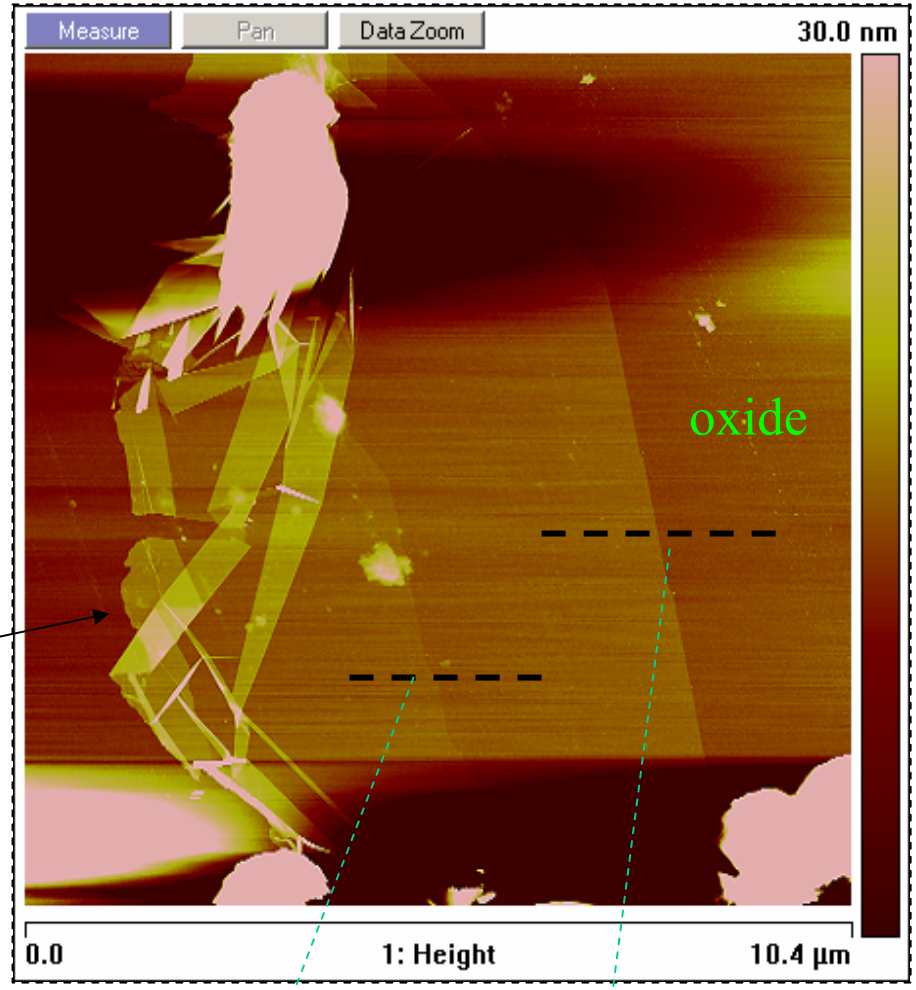


Sample # 2

Optical Microscope Image (OM)



AFM Image



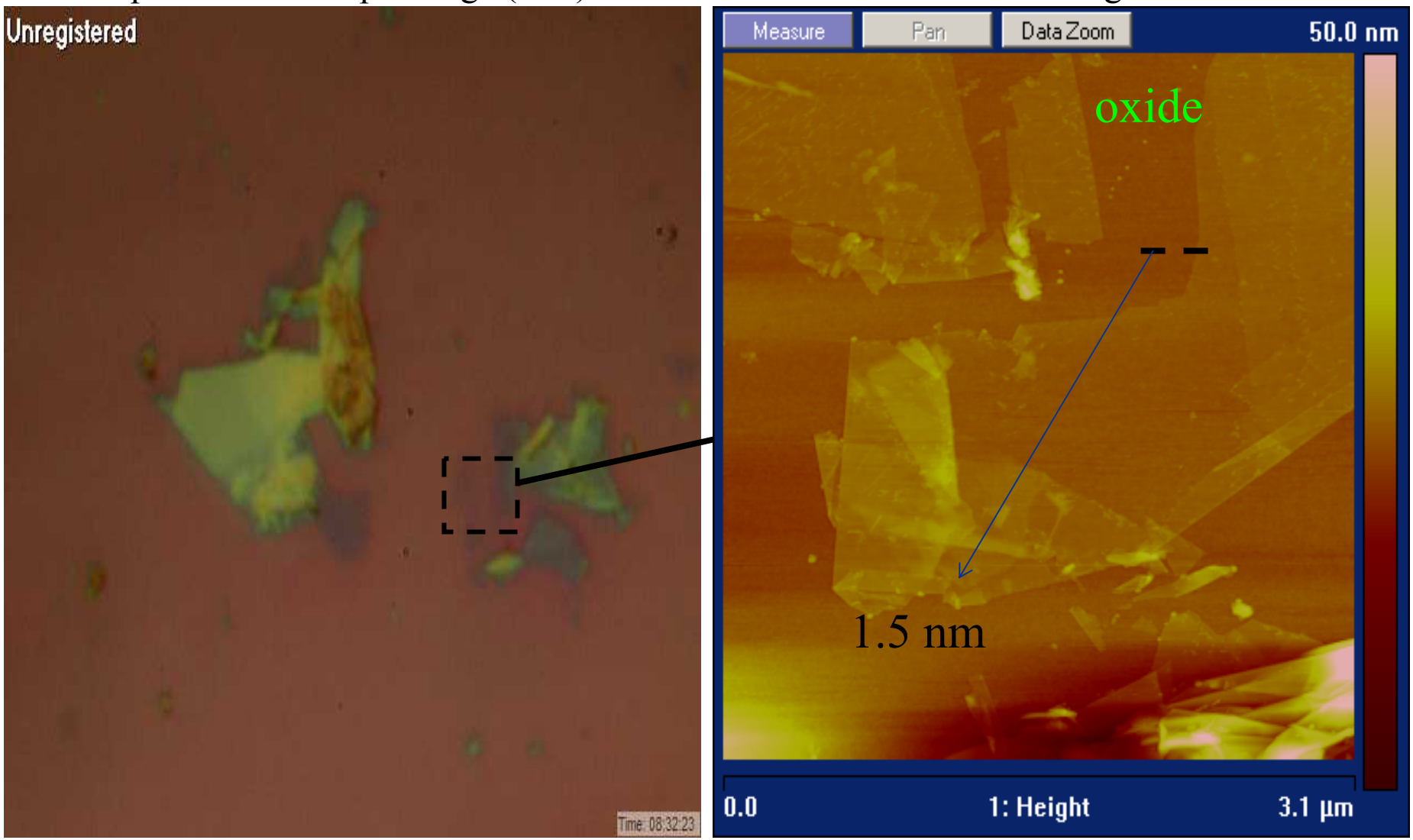
.85nm

1.5 nm

Sample # 3

Optical Microscope Image (OM)

AFM Image



Summary and Outlook

- We confirmed the existence of Graphene
- Practical difficulty
- Use EFM (apply voltage at the tip) to measure Density of States (DOS)
- Pattern Contacts using Electron Beam Lithography