

Quantum Electrodynamics in Graphene

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Physics REU 2006 Univ. Of Washington

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Graphene, a single layer of graphite, is a source of remarkable quantum properties. This two-dimensional structure was studied immensely by the theoreticians. The band structure of graphite was first calculated by P.R Wallace in 1947 [3]. Graphene was assumed not to exist freely until Novoselov et.al in 2005 reported its discovery and the anomalous features it exhibits [1].

Graphene has a honeycomb lattice structure of carbon atoms in sp^2 hybridization state. There are two carbon atoms in a unit cell and each atom contributes a free electron. The Brillouin zone of graphene is hexagonal in shape (Fig 1.). The unhybridized $2P_z$ orbitals give rise to valence and conduction band. The energy band structure of graphene is shown in Fig 2.

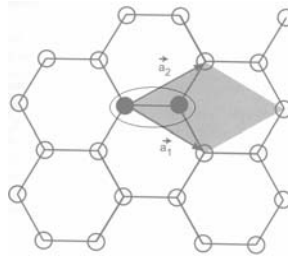


Fig 1. Lattice structure of graphene in real space [4]

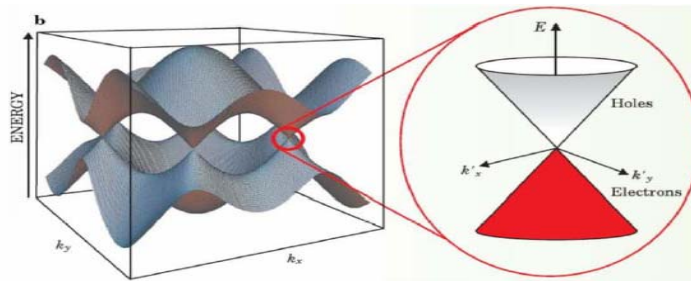


Fig 2. Energy band structure of graphene. The energy bands become cone shaped at the corners of BZ. [5]

The band structure of graphene is unique in the sense that at the six corners of the Brillouin zone, the valence and the conduction band meet at a point. The Fermi energy

level passes through these points. Since the bands meet at the corners, the charge carriers in graphene have a linear energy dispersion curve in the vicinity of these points. Only two sets of the corner points are inequivalent (K and K') and these points are called the Dirac Points. The electron dynamics in graphene obey the 2D Dirac equation, which describes the behavior of a $1/2$ spin particle in the relativistic regime. The energy of a particle having linear spectrum is given by,

$$\varepsilon = \frac{\hbar k}{2\pi} v_f, \quad (1)$$

where v_f is the fermi velocity, which is of the order of 10^6 m/s . The dispersion relation of charge carriers in an ordinary conductor is given by

$$\varepsilon = \frac{\hbar^2 k^2}{2\pi m}. \quad (2)$$

The charge carriers in graphene thus mimic relativistic particles, which are massless and travel at the speed of light. Thus, they can be rightly called as massless relativistic Dirac fermions. The effective mass of the charge carriers in graphene vanishes at Dirac points and they travel at the effective speed of light.

When a magnetic field is applied perpendicular to the 2D graphene surface, the Landau Level (LL) spectrum shows abnormal behavior compared to other 2D conductors. Landau levels refer to the quantization of electron energy under a magnetic field. Graphene exhibits a LL index of $N = 0$ at energy $E = 0$. This anomaly leads to various other anomalous quantum properties in graphene. Graphene exhibits an unconventional quantum hall effect different from ordinary 2D conductor. The Hall conductivity in graphene is given by,

$$\sigma_{xy} = \frac{4e^2}{h} \left(N + \frac{1}{2} \right), \quad (3)$$

The equation has an additional half term compared to quantum hall conductivity in ordinary 2D conductors. Hence, the hall plateaus appear at half-integer filling factors rather than integer filling factors. Fig 4. shows the quantum hall effect in graphene.

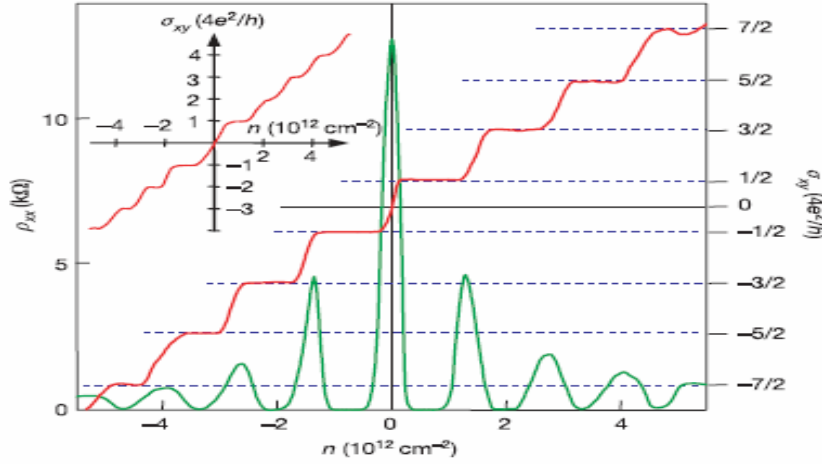


Fig. 3 Quantum Hall effect in graphene. The plateaus appear at half-integer filling factors. The inset graph shows quantum hall effect for a regular 2D conductor, with plateaus at integer filling factors [1].

Another interesting feature in graphene is the existence of minimum conductivity, even in the absence of charge carriers. At the Dirac points where the two bands meet, carrier concentration is assumed to vanish, and hence conductivity should be zero. However, it is observed that the conductivity in graphene exhibits a minimum value or that the resistivity exhibits a maximum value [1]. The maximum resistance is given by

$$\rho_{\max} = \frac{h}{fe^2} \quad (4)$$

where f is the degeneracy, and graphene is four-fold degenerate (two-spin and two-valley degeneracy). One explanation for the existence of a minimum conductivity is the Mott's argument, which states that mean-free path cannot be smaller than the Fermi wavelength. Under low magnetic field, graphene exhibits Shubnikov de-Hass oscillations (SdHO). However, SdHO also shows anomalous behavior. The longitudinal resistance displays maxima rather than minima at integer filling factors. Thus, graphene exhibits a berry's phase of π with respect to SdHO oscillations [1]. The berry's phase may be related to extra half term appearing in the Hall conductivity. Bi-layer of graphene exhibits different quantum features compared to single layer of graphene. Very recently, it has been reported that a bilayer of graphene exhibits a berry's phase of 2π and another unconventional quantum hall effect. [6].

The goals of the project were to reproduce graphene on a silicon dioxide substrate. We also planned to find a better way to deposit graphite and a convenient and faster method to identify graphene. By patterning terminals on the graphene, we planned to take transport measurements and confirm the results. After doing these basic frameworks, we intended to use graphene as bench top system to study quantum electrodynamics. Various quantum properties including Klein paradox could be studied using graphene. We also planned to adsorb alkaline dopants to see whether the Fermion properties could be manipulated.

To reproduce graphene various techniques of deposition was used. A silicon wafer with a coating of oxide (thickness 450 nm) was used. The chips are cleaned in acetone and IPA for about five minutes. Graphite was deposited on the chip by plain rubbing using tweezers. The rubbing force was varied ranging from gentle touching to

hard pressing. The angle of rubbing was also changed to observe variations. Graphite was placed between two chips and the chips were rubbed to observe any improvements. Wet deposition under liquids like water, acetone, isopropyl alcohol, and n-hexane was experimented. The wafer was heated in order to see whether removal of moisture would improve the chances of getting a single layer. Plain rubbing followed by cleaving of graphite flakes using another silicon chip was also tried.

The preliminary analysis of the prepared samples was done using an optical microscope. We used a Meiji Optical Microscope which has an optical camera connected to it. The video feed from the camera can be viewed on a computer screen. The sample is scanned slowly to see whether thinner layers are present. The thinner layers are those that are hardly visible under the optical microscope. Usually thinner layers are found on the edges of thicker graphite flakes, which consist up to 20 layers. The snapshot of the spots are taken. Snapshots of surrounding area and features are also taken to identify these spots later. Calibrating the chip with grids to locate the spots was tried but it was discontinued because thicker graphite flakes were deposited in these grids. Once a thinner layer is observed under the optical microscope, further analysis is done using an atomic force microscope. We used a Veeco Dimension 3100 Atomic Force Microscope. The AFM consist of a scanning probe microscope (SPM) and a control unit. The SPM has a cantilever, which vibrates at or near its resonant frequency. The cantilever has a tip at the end, which taps on the substrate. We used the tapping mode to scan the surface of the sample. A solid-state photo diode shines a laser light on to the end of the cantilever. When the tip encounter a raised feature, the cantilever deflects and the change in the intensity of laser light is measured by the photosensitive diode (PSD). The electronic

detection components attached to the PSD convert the deflection into electric signals. These signals are sent to the control unit, which compares the incoming signal from the SPM against a stored value. The differential voltage is sent to the piezo electric scanner and the cantilever's vertical position is changed in such a way that it vibrates at its resonant frequency. The vertical shift is stored as a function of the tip position and is translated as the height of the feature present on the sample.

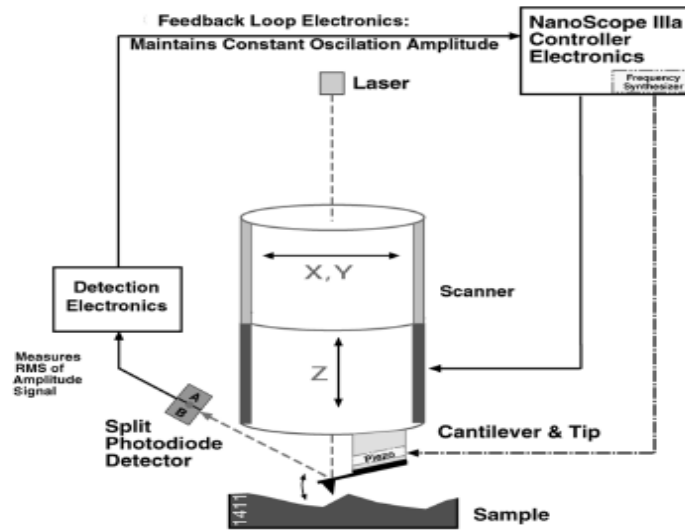


Fig 4. The diagram shows basic functioning of an AFM [7]

The image of the particular spot is taken using the AFM. The image is analyzed using the Nanoscope software. The differential height of the layers is measured by *section* analysis. The differential height between two successive graphite layers should be 0.35nm and the differential height between the dioxide substrate and graphene layer can vary up to 0.7nm due to water layer on the chip and van der Waals interaction between silicon dioxide and graphene layer. We were able to produce one sample having graphene layer using the technique of plain rubbing followed by transfer (Fig 5).

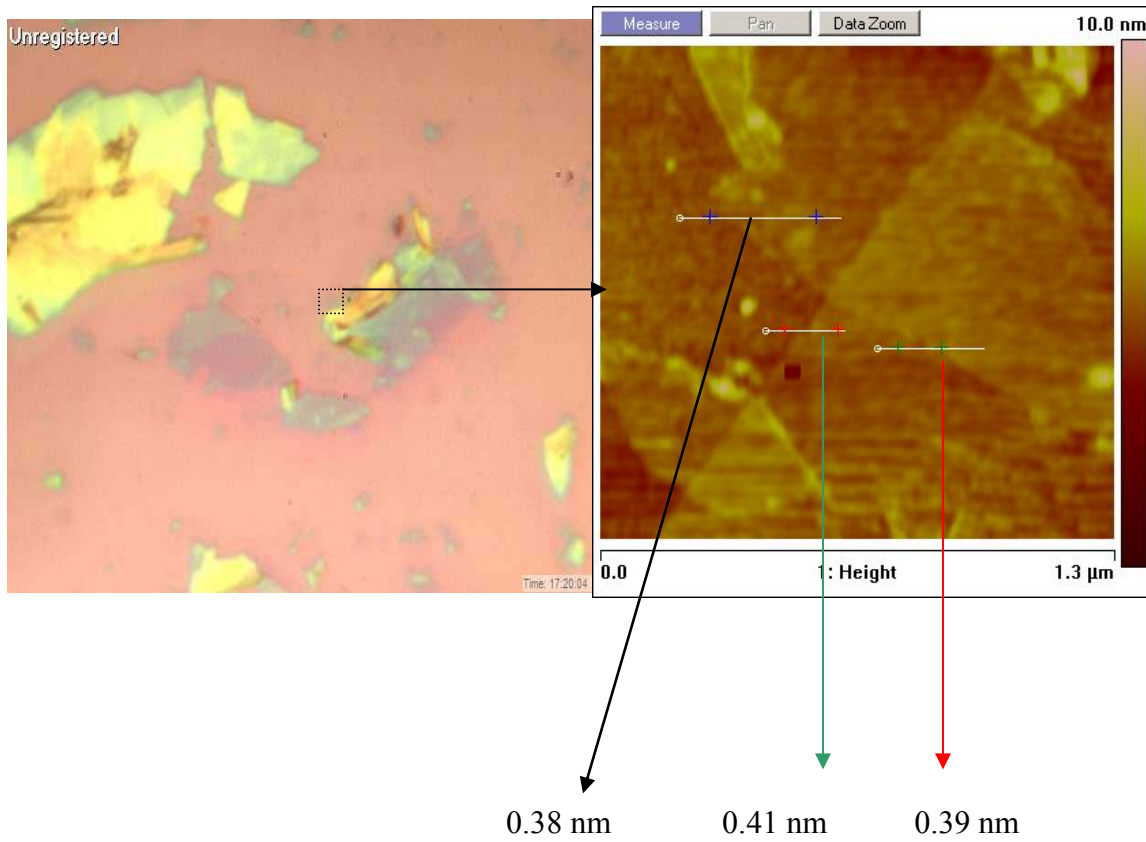


Fig 5. The figure shows a single layer of graphite. One layer of graphene is lying on another graphene layer. The graphene layer was found to be torn and creased and is lying close to a bi-layer.

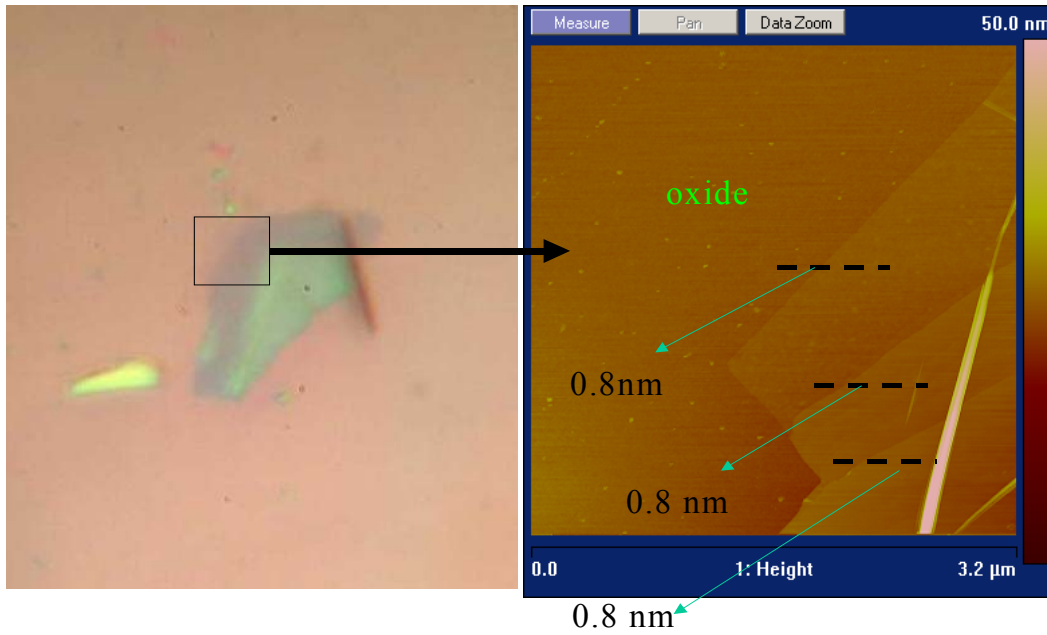


Fig 6. The figure shows the AFM image (right) of the selected portion of the optical microscope image (left). The first layer in the AFM image might be a single layer, however it cannot be confirmed because the successive layers show a differential height of $\approx .8nm$ instead of $0.35nm$. The layers might be folded which results in an increased differential height of the layers away from oxide substrate.

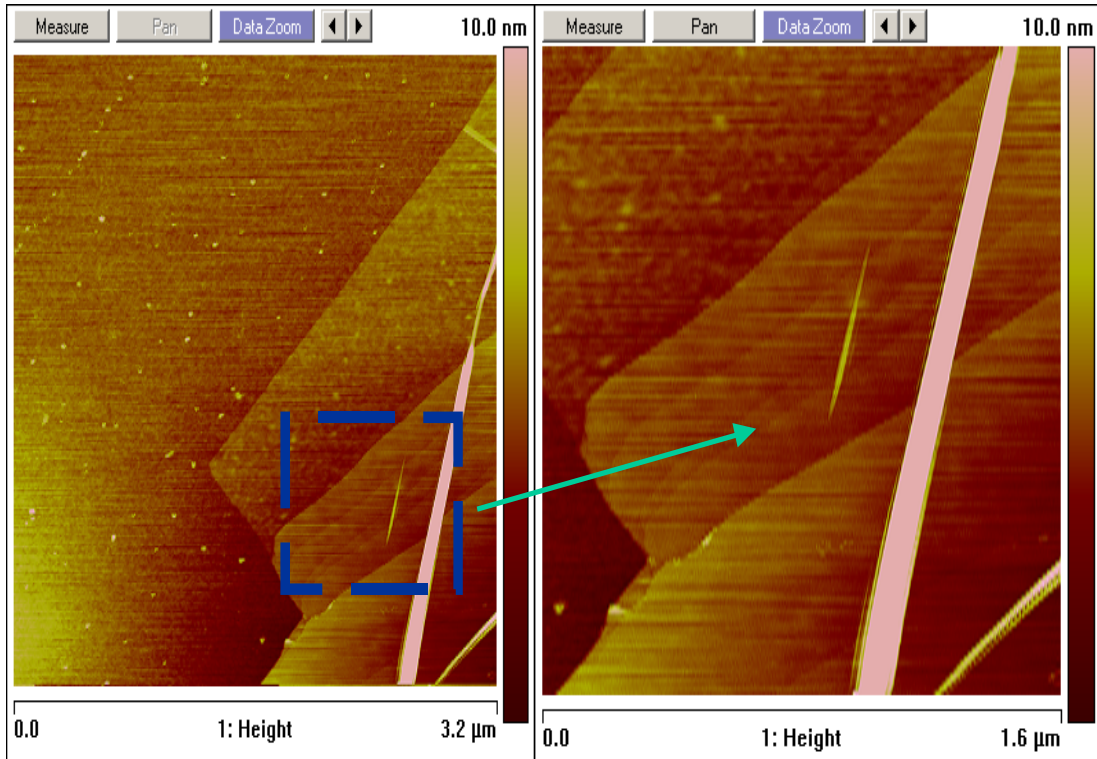


Fig 7. The figure shows creases and bumps in the second layer in figure 5. These features introduce noise in the image.

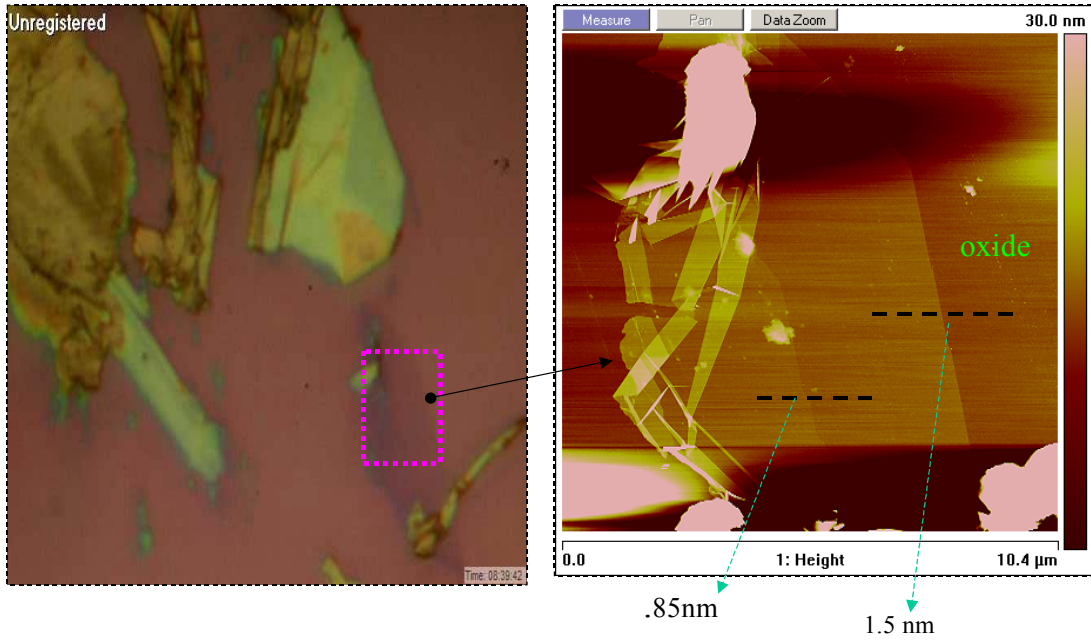


Fig 8. The outer layer might be 3-4 layers. Here also the folding of layer may be the reason for the increased differential height between the two graphite layers.

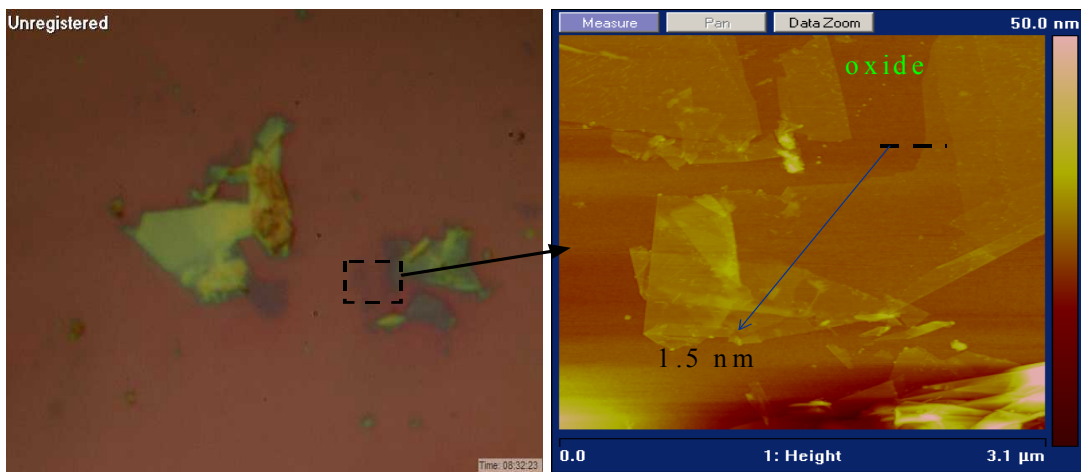


Fig 9. Another sample showing 3- 4 layers of graphit

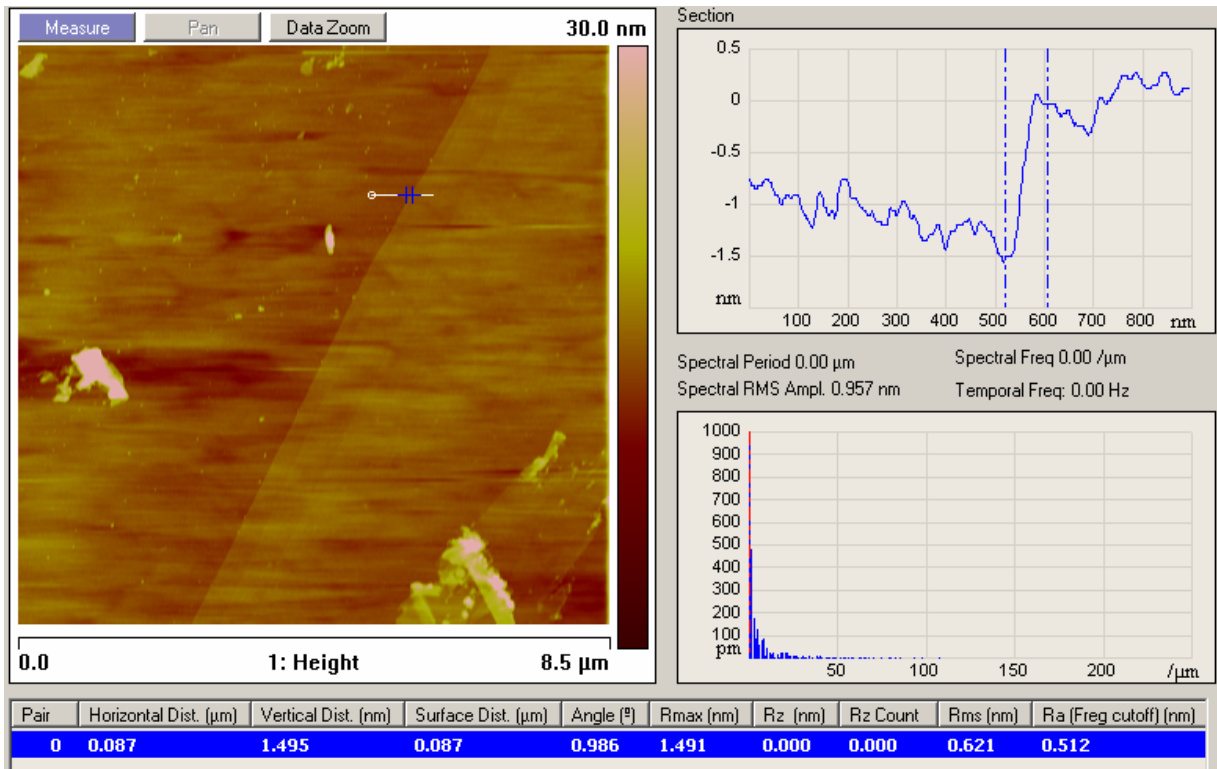
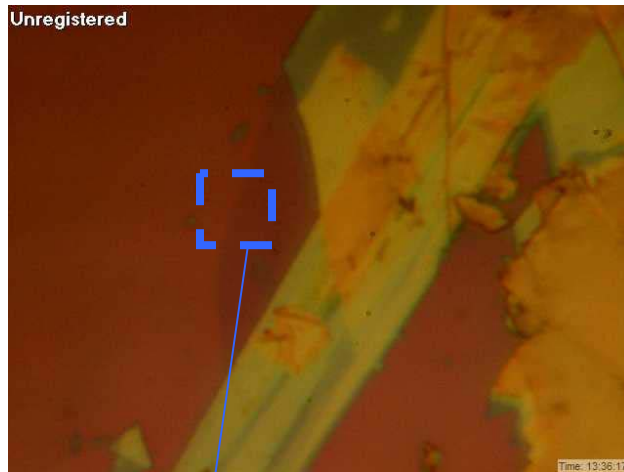


Fig 10. The figure shows the section analysis of a FLG(3-4 layers)

Thus, we were able to confirm the existence of a single layer of graphite. The inconsistency in obtaining thinner layers of graphite makes it difficult to conclude, which

method is better suited to produce graphene. We wish to implement EFM technique to analyze the density of state of graphene, so that a better method to identify graphene can be developed. EFM technique has been used to measure the local density of states in carbon nanotubes [7], and it could be used in graphene. Once we are able to produce single layer of graphite, we wish to pattern contacts using electron beam lithography (EBL) to make transport measurements.

I would like to express my sincere thanks to Dr. Cobden in allowing me to work in the lab during the summer, and designing a project that is challenging and competitive. I hope that further progress will be made during the coming months. I would also like to thank Dr. Fain for his abundant supply of graphite and his expertise on the material. I am also indebted to Andrew Jones for his help in starting the project and both Andy and Jiang Wei for the AFM training they provided. Sincere thanks to the UW Physics Department, Dr. Seidler and the NSF.

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