Probing inside the atom and investigating its structure, science transcended the limits of our sensory imagination. From this point on, it could no longer rely with absolute certainty on logic and common sense.

....Fritjaf Capra, The Tao of Physics
Graphite-New Foundation for microelectronic circuitry

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Background ...

Carbon nanotubes - evolving interest ....

• are graphene sheets rolled into cylindrical structures
• excellent conductivity (1000 x more conducting than Cu)
• ballistic conducting properties (next best after superconductors)
However ..

- Properties of CNT depend on rolled orientation, direction (chirality factor), SWCNTs could be metallic or semiconducting
- Difficult to control their size, orientation & structure during preparation
- Difficultly integrating carbon nanotubes with circuitry using bulk production processes
- high resistance at interface connections
So, why not graphene?

- Is a single layer of graphite
- Graphene has electrical properties as good as CNT
- Flat graphene sheets are zero gap semiconductors and provides metallic path easily
- Demonstrates 2DEG properties in contrast to 1DEG properties of CNT
Making graphene sheets - current methods

- repeatedly peeling off layers from HOPG using adhesive tape
- suspension of graphitic particles in acetone, sonicating the solution and running a sample through it
- Chemical vapor deposition
- Thermal desorption of silicon from silicon carbide wafers
Growing Graphene in Gatech..

- Uses the thermal desorption process
- Heating of 4H silicon carbide wafers in high vacuum conditions in specially designed induction furnace to drive off the silicon atoms
- Silicon terminated phase and carbon terminated phase both being used
Research Project- the big idea..

- Hydrogen etching of silicon carbide wafer to clean the surface
- Graphitization by vacuum heating to drive off silicon atoms from the surface
- Depositing contacts
- Spin coat with photo resist material
- Electron beam lithography to pattern circuits
- Etching the pattern
- Studying the electrical transport mechanism of the patterned device or circuit
The ultimate goal

- To demonstrate capability of graphene as a suitable material for electronics by investigating its electron transport mechanism
- pattern microelectronic circuitry in as small as a 10 nm scale

Dr. De heer’s team has successfully patterned an all graphene planar FET device; and have studied graphene circuitry with feature sizes of about 80 nm
Instrumentation and Techniques

- Atomic force microscopy - used to study the sample surfaces before and after graphitization to learn more about terrace structure and step flow processes.
- Electric force microscopy - used to study contacts in patterned circuit and electric potential imaging of conducting samples.
LEED Imaging and analysis

The low energy electron diffraction patterns of the sample surface after the graphitization process is analysed to look for graphite diffraction spots. The arrangement of these spots at different energies of the electron beam can be used to give an idea of the restructuring process of the surface during the thermal desorption process of the silicon.

LEED images of surface sample

LEED experimental setup
Scanning Electron Microscope

The scanning electron microscope uses an electron arrangement and electromagnetic lens systems to focus the beam on to the sample. The interactions of the electron beam with the sample can be studied by collecting the back scattered electrons or the secondary electrons and the information can be used to map out the surface properties of the sample. The SEM images can be used to identify the conducting and non conducting of the sample. Since graphite has conducting properties as compared to silicon carbide, the SEM images can be used as a reference to identify the graphitized regions of the sample.
Electron Beam Lithography EBL

Sample surface cleaned in ultrasonic vibrator
Surface spin coated with photoresist at very high speeds to get a nano layer
Solvent evaporated by heating

Pattern etched by using electron beams in a SEM
Hall effect analysis...

Graphene is expected to show quantum mechanical hall effect at low temperature and high magnetic field; The experimental set up uses magnetic fields as high as 9 T and has sample at temperatures as low as 4K by using liquid nitrogen and helium. The Hall resistance as a function of the magnetic field is plotted and identification and analysis of Landau levels can be used to get information about ballistic transport properties of graphene.
The processes....

- AFM images

start

Hydrogen etching to clean surface

SiC sample surface –AFM image

Sample surface after hydrogen etching- AFM image
Graphitization of the sample by heating in vacuum

- Focus on modifying the furnace design and controlling conditions of heating to result in huge flat terraces and graphene layers as wide as possible.
My role:

- Generally acquired a broad knowledge base by working on AFM, SEM and LEED operational techniques and analysis
- Specifically worked on one sample subjected to the graphitization process to look for gradient in properties or step characteristics
- Took AFM images of different locations of the sample after the graphitization process
- Took images along three different directions of the sample; x, y and diagonal
The process ..

- The SEM image of the sample was used to identify the conducting and non conducting regions of the sample.
- The SEM images were used as reference to choose directions and locations of scan for AFM imaging.
- Additionally, with the help of Dr. Conrad, the LEED images of the sample were also taken to help interpretation of the graphitization process in the sample.
Results..

AFM images of the sample along a diagonal direction

LEED images of the sample

Spot pattern due to SiC
Discussion of results

- The AFM images show a marked difference in the step structure and graphitized regions in the images taken in the center of the sample and the edges of the sample.
- However I could not interpret the image in terms of step flow characterization.
- The data collection should be done over repeated samples to ascertain any step flow behavior or graphitization pattern.
- It was however interesting to note change in terrace structures with variations in the controlling factors of the graphitization process by working with various samples.
- The LEED pictures only showed SiC diffraction spots generally attributed to a 3 x 3 reconstruction of the silicon carbide; it did not reveal any diffraction pattern due to graphene. However since images could not be taken at various locations of the sample as desired due to the sample holder complications, information about the sample remains incomplete.
- The OJ(Auger) spectrum showed carbon peaks at two different locations indicating that the sample surface has been graphitized more towards the edges than at the center.
The experience..

- This entire program has been a very rewarding experience for me. I have learnt a lot of interesting things about general research techniques and methodology. My experience in being with Dr. Conrad and Kevin as they assembled The LEEDS and worked through the UHV procedures was interesting. Since this project involved a whole lot of experimental techniques in one of the emerging fields of interest, nanotechnology, it helped me gain a good perspective into how things are shaping up in the investigative methods of nanotechnology.
There is always something in nothing ..... 

What is UHV? Pressures lower than 10-9 Torr

UHV hardware...
Combination of pumps in series or parallel to take it all the way down
Use of special copper gaskets to act as vacuum seals
Stainless steel used for core because it is strong, easy to machine, provides good welding joints
Quartz glass used for windows because of low thermal expansion coefficient

UHV procedures...
Baking at temperatures 200-400 C to remove water and hydrocarbons from walls
Outgassing is minimized by careful selection of materials and baking to a high temperature
Leak detection is done by spraying helium in the suspected locations and analysing using a fixed focus mass spectrometer
Future breakthrough...

- Optimizing oven parameters and repeating and refining the process to get truly 2D huge flat graphene layers
- To successfully pattern circuits on graphene as small as 10 nm using advanced EBL techniques
- To understand electron transport mechanism in graphene ribbons
Lesson Plan - Nanotechnology

- An introduction to nano dimensions and scanning probe microscopy by modeling the scanning techniques;
- To help students design a model that simulates to a certain degree the fundamental principles of electric force microscopy;
- To include mini research components on scanning probe techniques at the nano level.
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