Electrical Characterization of 2D Materials

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Abstract: Graphene is a promising material for use in flexible, high speed electronics due to its unique structure and electrical properties, Among other characteristics, it is said to have an unusually high electron mobility and a tunable Fermi level. Graphene transistors could transform the field of flexible, high speed electronics but an in-depth electrical characterization of the material is needed.

I. Introduction

Graphene is a two dimensional allotrope of carbon with a honeycomb structure consisting of benzene rings. A band of σ bonds between carbon atoms accounts for the structural flexibility of graphene, as well as other allotropes of carbon such as graphite. Graphite is composed of stacked layers of graphene held together by weak van der Waals forces. Monolayer graphene was originally detected in 2004 at the University of Manchester by using scotch tape on a graphite substrate [2].

Graphene is considered to be a semimetal due to its unique electronic properties, the most important of which centers around its Dirac electrons. Dirac electrons are electrons that follow the Dirac equation, meaning they are particles with mass that behave like massless particles of light whose energy dispersion is linear instead of parabolic. However, these electrons move at normal speeds that are about 300 times less than that of light. These electrons are also referred to as Dirac fermions due to their half-integer spin. These Dirac fermions behave differently than normal electrons. Under a magnetic field, they undergo phenomena associated with the integer quantum hall effect [1]. They are also insensitive to external electrostatic potentials as seen by the Klein Paradox, where electrons continue to move through barriers of differing potentials without external interference [4]. These potential differences can result from disorder caused by ionized impurities in the substrate, molecules absorbed by the graphene surface, or ripples due to graphene's soft nature [1].

Graphene has also been known for its controllable Fermi level. The Fermi level refers to where in the band structure of a material electrons can exist. The Fermi level equals zero in the middle of the band gap, between the conduction and valence bands. Due to graphene's semimetal nature, its conduction and valence bands overlap slightly, forming an X shape. The point of intersection is called the Dirac point, where the Fermi level is equal to zero. In graphene, this level can be tuned by applying a gating voltage which modifies the electronic structure by either increasing the number of electron charge carriers or hole charge carriers [3].

Research Question: The question to be addressed is how to verify monolayer graphene, determine sheet resistance through the use of metal contacts and two-point probe analysis and fabricate graphene channels to be used to measure electrical properties such as resistivity and electron mobility.

Motivation: The motivation for this research comes from the relatively new discovery and isolation of graphene and its potential as a main component in enhanced electronic devices. Graphene's unique electrical properties and its unusually high electron mobility could lead to the development of flexible, high-speed electronics.

II. Methods

Experimentation was divided into two phases. For the first phase, a graphene device with electrical contacts was fabricated. Graphene-coated substrates composed of a graphene layer on top of 300nm of SiO_2, and a thick layer of Si were obtained. Raman spectroscopy was used to ensure the substrates were composed of monolayer graphene. A thin layer (approximately 1300 nm) of photoresist (PMMA) was applied to the graphene using a spin coater at 4500 rpm for one minute. Using Raith's CAD software, a design consisting of 50um squares separated by varying distances was created. Using electron-beam lithography (EBL), the photoresist was exposed at an acceleration voltage of 30kV. The design was then developed by placing it in methyl isobutyl ketone (MIBK) for one minute, followed by isopropyl alcohol (IPA) for one minute. This processes removed the cured PMMA in the desired pattern created by the Raith CAD software. The samples were taken to the National Institute of Standards and Technology (NIST) for gold (Au) deposition through physical vapor deposition using a thermal evaporator. A layer, approximately one third as thick as the PMMA layer, was applied to the entire graphene square. In order to form gold contact pads, the square was placed in acetone for three hours to remove PMMA and excess gold, leaving behind the contact pad design.

A probe station consisting of two micromanipulators was used to characterize the sheet resistance of graphene. Using an optical microscope, the micromanipulators were placed on two contact pads and a voltage sweep from -3 V to 3 V was performed using a Keithley 2400. This resulted in measurements of current at 50 different voltages in the interval. Total resistance, which includes sheet resistance and contact resistance between the micromanipulators and the gold contact and the internal resistance of the multimeter, was calculated from these I-V curves using Ohm's Law. At a distance of zero between gold contacts, the only resistance that would be measured is the contact resistance, and internal multimeter resistance. Thus, a plot of resistance as a function of distance was created and extrapolated to distance equals zero. This contact resistance was subtracted from calculated resistances.

The second phase aimed to measure the resistance of graphene through a channel to calculate its resistivity and electron mobility (μ). A CAD design consisting of 40 um thick trenches was created to isolate 'graphene ribbons' in order to move current through a predefined channel of graphene. Trenches surrounded two graphene pads of 100 μm x 100 μm and a 2-6 μm wide channel (lengths 40-120 μm) (Fig 1).

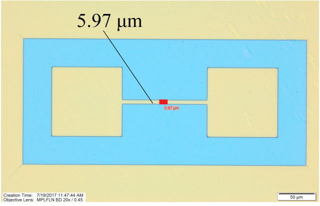

Figure 1 Trench after EBL

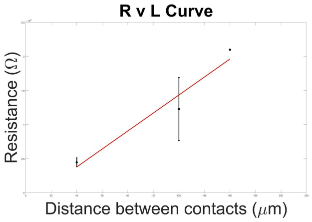

Figure 2 Resistance/Length curve

EBL and an AutoGlow Plasma System were used to etch away graphene in the trenches to create an insulated region of SiO_2 around the channel and graphene pads. A profilometer was used to measure the thickness of PMMA at 30 second intervals of plasma treatment to characterize the etching process. Raman spectroscopy was used on an etched sample, an unused graphene substrate, and a SiO_2 wafer to determine if the graphene was etched, leaving SiO_2 trenches.

III. Results

Raman spectroscopy confirmed our samples were indeed monolayer graphene (Fig 3a). From the data collected in the first phase, a resistance vs. length curve was created. However, due to the nonlinear nature of the measurements, the curve could not be extrapolated to zero and the sheet resistance could not be determined (Fig 2). In the second phase, graphene was successfully etched to create ribbons (Fig 1). Raman spectroscopy was used to verify that only SiO_2 remained in the trenches. While attempting to etch the graphene, a profilometer was used to characterize the thickness of PMMA at different time intervals under an AutoGlow Plasma System to determine the extent of material removed as a function of time (Fig 3d).

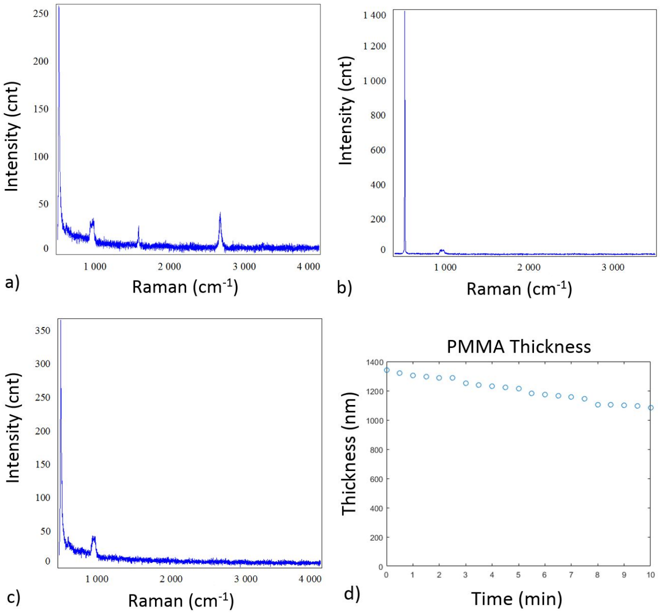

Figure 3 Raman spectrum of a) graphene substrate on 300 nm SiO_2 b) SiO_2 substrate c) etched graphene. d) PMMA thickness over time. For Raman spectroscopy, graphene has characteristic peaks at 1580 and 2690 cm^{-1} while SiO_2 has peaks at 520 and 950 cm^{-1}. The etched graphene has only SiO2 peaks, proving that graphene was etched successfully

IV. Discussion/ Conclusion and Future Considerations

Raman spectroscopy was successfully used to verify monolayer graphene. Gold contact pads were fabricated to measure sheet resistance but results were inconclusive. Graphene ribbons were successfully fabricated using EBL and a plasma system. Raman spectroscopy was used to ensure all graphene was etched from the trenches. In future studies, a second round of EBL will allow us to fabricate contact pads on either side of graphene channels in order to measure resistance through a channel and calculate resistivity and electron mobility. A third phase would allow the fabrication of graphene transistors whose electrical properties could be compared to modern silicon transistors in order to assess the possibility of graphene-based electronic devices.

V. References

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