

Chemical Bonding Elucidation of Graphene Films Synthesized by Low Temperature CVD-Growth

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Abstract

The grapheme was layers synthesized via chemical vapor deposition (CVD) utilizing a carbon source from a polymer film matrix with an organic solvent. In particular, the carbon (C) source for CVD synthesized graphene was chlorobenzene solvent in a poly(methylmethacrylate) (PMMA) matrix. The catalytically deposited multi-layered graphene on copper foil (Cu) was characterized by Raman spectroscopy. X-ray photoelectron spectroscopy (XPS) was used to analyze the bonding environment over large areas of the graphene sheet on the copper foil after growth. This analysis revealed the bond energy of C and contributions of other elemental species. The second most abundant element after carbon was found to be oxygen (O) atoms. This observation is related to the problem of removing all the O species from the surface of the catalyst in the cleaning process. One of the key results is that the energy binding of the level C 1s in a sp^2 structure is about 284.3 eV. The carbon sp^3 core level peak is found at 284.9 eV. It is significant and indicates the grapheme presence. Further tests, including near-edge X-ray absorption spectroscopy (NEXAFS), verified the presence of C atoms. The NEXAFS data was providing better bonding information and variation of electronic structure of the carbon layers as a function of growth temperature (T_{growth}) was observed.

Introduction

The synthesis of several layers of graphene can be done by means of various types of precursors (gaseous, liquid or solid). Because of its higher purity compared with solid and liquid [1–7], hydrocarbon gas precursor is a preferred as source of carbon for grown the graphene layers. In recent years, research has focused on sources of liquid carbon because of their availability and lower cost compared to carbon sources of gaseous [8-11]. The formation of graphene was related to the energy of C-H bonds in molecules source and the breakdown temperature of source molecules was selected. C-H bond energy is 440 kJ mol^{-1} which is large and it allows the synthesis of graphene from methane (CH_4) at high temperature (about 1000°C). Other sources of hydrocarbons such as polymethylmethacrylate (PMMA) with chlorobenzene, PMMA and benzene to reduce the temperature of the synthesis are the best way to synthesize graphene. Nevertheless, lowering the CVD temperature of graphene formation results in more defects, which in turn affects its physical properties.

Kashiwagi et al. [12] studied the thermal degradation of PMMA. The first step of thermal degradation of PMMA, polymerized by the free radical method, is a weight loss starting from about 165°C and it is associated with the breaking of the head-to-head links (H-H). Moreover, the (H-H) bond dissociation energy was less than that of the (C-C) backbone bond due to the inductive effect of the adjacent ester group and the high steric hindrance. The thermal degradation occurs at about 270°C and is characterized by scissions at the unsaturated ends. This is caused by a termination via disproportionation. The vinyl group is attached to a homolytic scission beta on the PMMA structure. The last breakdown stage at about 350°C can be assigned to the random scission of the polymer chain. Thermal degradation of PMMA with molecular weights of 36 and 179 kg mol^{-1} , polymerized at around

220°C [13-16] with benzoyl peroxide as a radical initiator, took place with an activation energy of 130 kJ mol⁻¹. The thermal degradation of PMMA is affected by the stereoregularity and molecular weight of the macromolecules.

Thermal decomposition of chlorobenzene was complex kinetic processes. Furthermore, there has been more concern on the chemical and thermal reactions of chlorinated organics due to the production of chloro-oxycarbon species or toxic/carcinogenic compounds in wastewater effluent [10]. Hydrocarbon products such as acetylene and ethylene are produced in a heat reaction with chlorinated hydrocarbons in a hydrogen atmosphere. This results in the total conversion of the alkyl chlorocarbon species to HCl [11]. In the heat reaction, the radical species of H₂ atoms are added to the aromatic ring, resulting in the synthesis of chlorobenzene with a suitably low activation energy for the reaction path [12]. The Chlorobenzene-PMMA film can be used as a good low decomposition carbon source to lower the temperature for graphene synthesis. The graphene layers can be deposited at low temperature with benzene as liquid source or PMMA as solid source [6, 7]. The production of graphene is a fine balance between bonding energies, the molecular structure of carbon processing and temperature increase. Ethylene and acetylene were selected as gaseous carbon precursors for low temperature growth because of their lower C-C pyrolysis temperature than methane [13]. The atomic structure has a hexagonal arrangement of carbon atoms. Graphene and benzene are involved. The C-C bond length of the benzene shows that the atomic radius of carbon in the graphite layer is the three alternate atoms of the benzene ring while the other three carbon atoms are the radius of the covalent double bond. Carbon nanotubes are a class of materials based on a conjugated network of aromatic rings, with benzene as the smallest molecule in this class [15, 17]. The low activation energy of benzene allows grown of layers from grapheme film at low temperatures of ~300°C [5, 16]. Large area graphene films were synthesized as a continuous monolayer on Cu foil using CVD under atmospheric pressure with benzene as a carbon source at temperatures between 100 and 300degC. The modeling of liquid chlorobenzene shows a clear interaction of benzene rings and chlorine aggregation, which can be described by molecular arrangements at small distances between chlorine atoms around 25°C. It was lead for agglomeration of molecules chlorobenzene [18, 19].

In our study, the multilayer graphene was grown at low temperature growth (400-700°C) on pre-annealed copper foil (~900°C). Raman spectroscopy showed the presence of graphene layers, i.e. multiple carbon layers on the catalyst. Transmission electron microscopy (TEM) after the graphene transfer showed a hexagonal structure of homogeneous layers of graphene with small domain sizes. Also, a unique way for studying the mechanism growth at low temperature is grown of layers graphene from a carbon source that content organic solvents and polymers. The method provides new insights into how graphene is formed and offers opportunities for more sustainable production methods. Future studies can be performed to optimize the conditions for improving the quality and scalability of synthesized graphene for different applications in electronics and material sciences.

Experimental section

PMMA was purchased from Aldrich and dissolved at a concentration of 100 mg/mL in chlorobenzene. The PMMA-chlorobenzene solution was then drop-casted on a quartz slide and loaded into the tube furnace of CVD as a source of carbon. The catalyst had prepared by thermal annealing of 25 micron thick copper foil (Cu) at 900°C under atmosphere of hydrogen (H₂)/argon (Ar) for 1 hour with flow rates of 50:100 sccm respectively. The copper foil was electrochemically polished before thermal annealing in a home-made electrochemistry cell to obtain a smoother and more planar catalyst surface, which affects the growth of graphene layers (**Supplementary Figure S1**) [19, 20]. Hydrogen (H₂) gas has been used to purify the surface of copper and reduce oxidation during the pre-annealing step of graphene growth [4, 20]. The flow rate of Ar gas during thermal annealing was controlled for limiting and controlling the concentration of oxygen (O) in the CVD chamber [21]. The pretreatments induced the chemical reaction on the surface of Cu foils, which changed the morphology of Cu foils. The orange red to yellow Cu₂(OH)₂ can be generated during the polishing process. The chemical reaction yields Cu₃(PO₄)₂Cu(OH)₂ [22, 23]. The copper foil was washed with deionized water and ethanol after the process. Then it was dried with nitrogen (N₂) gas.

The chemical and physical properties of the sample surface were characterized with X-ray photoelectron spectroscopy (XPS), which is very surface sensitive. The cleaned copper foil surface was analyzed with non-monochromatic X-ray source (Omnivac) using Al K α (1486.6 eV) radiation to determine the elemental composition and chemical state of the sample. The Cu foil on the XPS substrate was investigated by survey scans at a pass energy of 100 eV. The pressure of operational in the chamber analysis during the illumination X-ray of the sample was basically 3.0 x 10⁻⁹ mBar, and the typical pressure was 4 x 10⁻¹⁰ mBar. Crystallographic structure of the material was analyzed by X-ray diffraction (XRD). This method was used to study the formation of crystalline domains in the Cu catalyst and the formation of crystalline domains in both unannealed and annealed catalysts were studied at different temperatures for one hour. The X-ray diffraction measurements were carried out on a Philips X'Pert MPD XRD apparatus with the sample inclined at 45° to the incoming beam and the source emitting Cu K α radiation with a wavelength of 1.5405 Å. The periodic planes of the crystal lattice scatter X-rays and produce a measurable diffraction pattern. Moreover, the thermal degradation of chlorobenzene solvent in PMMA matrix was characterized by thermogravimetric analysis (TGA) using Perkin-Elmer Diamond TG/DTA.

Graphene layers were deposited on cleaned copper foil at low temperature (400-700°C) under hydrogen flow rate (25-100 sccm) with carbon source heated at 180°C. Graphene quality film is characterized by Raman spectroscopy before the method wet of transfer. The analysis is related on the ratio of intensity I_G/I_{2D} which is essential to understand the characteristics of the Raman spectra of graphene, G band (around 1580 cm⁻¹) and 2D band (around 2700 cm⁻¹). The method is successfully applied to determine the number of graphene layers on the catalyst [24 - 27]. The quality of the graphene films in each growth condition was analyzed by Raman spectroscopy (Renishaw inVia Raman spectroscopy). This technique provides laser wavelengths of 325 nm (Helium-Cadmium), 514 nm (Argon-Ion), 633 nm (Helium-Neon) and 785 nm (Diode). The XploRA PLUS Raman microscope from HORIBA Scientific is utilized for perform

Raman mapping, which enabled the quality of graphene layers to be verified in an area of 40×40 μm. Add to this microscope with performance of atomic force microscopy (AFM) with a 532 nm green laser with 20 mW power, a numerical aperture (NA) of 0.7, and a spot size of 400 nm and a step size of 1 nm.

The atomic structure of the graphene layers was revealed by transmission electron microscopy (TEM) using a Jeol 2100 microscope operated at voltages of 80–200 kV and magnifications of 10,000–100,000. The thickness layers and morphology of the graphene surface was investigated by AFM using a Cypher AFM from Asylum Research. The properties of the graphene sheets obtained at low temperature from chlorobenzene-PMMA show the existence of a limited number of layers of carbon atoms, in a honey-comb configuration, as observed with this equipment.

Results and Discussion

The roll manufacturing's oxidation and pollution have had an impact on the purification of the copper foil surface. The oxygen gas concentration can lead to the formation of an oxidation layer that may grow during the copper foil thermal treatments in the tube furnace of the CVD system. This oxidation layer may be caused by air in the CVD tube, impurities in the gas source or slight environmental leaks. The copper foil was annealed in a mixture of hydrogen and argon gas at 900°C for 1 hour. This thermal treatment with high purity atmospheric gases can lower the level of oxidation on the samples over the surface (**see Supplementary Figure S2**). The figure shows the spectra of XPS for the Cu foil annealed compared to the Cu foil raw. The peaks at energy binding of about 284.4, 534.4, and 75.4 eV are attributed to C 1s, O 1s, and Cu 3p, respectively. The new Cu foil only shows 1.1 eV shift of C 1s peak after thermal annealing, while the peak intensity decreases with the increasing content of amorphous carbon. The intensity of the peak of O 1s has reduced considerably after treatment under the same conditions and the position of the binding energy shifts by 2.9 eV with respect to the sample standard [28, 29]. The investigation gives a firm support to the cleaning procedure after thermal treatment of copper foil. In addition, the O 1s spectrum reveals the properties of the oxygen functional groups on the copper surface. The sp³ carbon sites have a binding energy peak at about 285.5 eV and the hydroxyl group is indicated by a feature at about 286.6 eV. The carbonyl group appears at 288 eV and the carboxyl group at 289 eV [24, 25]. The peak of graphitic is also observed at around 291 eV. The main C 1s peak is composed of the peak of graphitic and a low level contribution from atoms of carbon in a non-graphitic environment.

It was found that thermal annealing of copper in a controlled environment of hydrogen and argon gas is optimal for removal of the layer of oxide from the surface of catalyst. The X-ray diffraction (XRD) study (**see Supplementary Figure S3**) indicated that this annealing process increased the grain size of copper, which reduced the number of grain boundaries. This leads to the minimization of the surface defect density and a significant reduction of the oxygen on the copper surface. Such purification is necessary for the efficient introduction of a surface catalyst for the formation of graphene. The temperature of the annealing process was optimized by conducting the procedure at four different temperatures in the range of 600–900°C, and the crystal structure of Cu foil after the annealing process was analyzed by

XRD. The crystallinity of copper is increased after annealing, as shown in Supplementary **Figure S3**, and the effect is more pronounced at higher annealing temperatures, i.e., 900°C, 800°C, 700°C and 600°C. The improvement of crystallinity is expected to promote the better growth of graphene. In addition, the size of grain for the Cu foil increased with the temperature of annealing at the (200) orientation [20, 30].

The degradation of thermal for chlorobenzene-PMMA has studied utilizing TGA. The decomposition of thermal for PMMA pure in powder form composite PMMA with chlorobenzene in the atmosphere of nitrogen is shown in **Supplementary Fig. S4**. PMMA-chlorobenzene for the thermal of pyrolysis, dried at air-dried and 180°C, was performed in the temperature range of approximately 30 to 520°C. The degradation behaviours of pure PMMA and films degraded in nitrogen were different. In the early stage of degradation, a small amount of breakdown molecules was detected in the sample under a nitrogen atmosphere, suggesting an initial weight loss. The samples were described as being in a condition of dried air at 180°C and a drop-costing wet condition for the source of carbon scenario during the insertion procedure into the tube furnace of CVD. The concentration of molecules chlorobenzene within the film of polymer had high initially and is illustrated as a drastic drop in the TGA-spectrum at the boiling point of the solvent (approx. 130°C). The C-H bond energy in benzene is 113.5 kcal mol⁻¹ at 300 K [26, 31–35]. Thus, the dissociation of chlorinated hydrocarbon is easy at high temperature. The average bond enthalpy of C-Cl, C-C and C-H are 338, 348 and 412 kJ mol⁻¹, respectively [27, 33]. Evaporation of chlorobenzene molecules from the air-dried polymer film showed thermal decomposition at about 180°C, above the boiling point (**Supplementary Fig. S4**). Moreover, the carbon source dried at 180°C showed pure PMMA degradation characteristics around 350°C. PMMA is degraded by random scission by a homolytic cleavage of a side group from methoxycarbonyl, followed by a β scission at ~ 350–400°C [9, 36–41]. The properties of polymer films obtained from solvent of organic may differ from those of the original bulk polymer. Moreover, the residual solvent properties of molecules in the polymer film are different. Polymer chains could trap the solvent molecules and this could reduce the α relaxation due to the plasticization effects [13, 42].

Layers of Graphene were synthesized on purified copper foil at different low growth temperatures (T_{growth} 400–700°C) with hydrogen flow of 50 sccm and the source of carbon was heated to 180°C (T_{source}). Before the wet transfer process, the synthesized grapheme for the quality has confirmed via Raman shift. In this investigation, the most important characteristic in the Raman spectra of graphene, the intensity ratio I_G/I_{2D} was used. The G peak is 1580cm⁻¹ and 2D peak is at 2700cm⁻¹. This approach is efficient for determine the graphene number layers (n GL) on the surface of catalyst [21, 43]. A typical Raman spectra and the mapping of CVD multilayer graphene were obtained, indicating the graphene layers on copper foil before being transferred into a target substrate. The characterization Raman clearly identified the G band and 2D band at around 1582cm⁻¹ and 2690cm⁻¹, respectively, as shown in Fig. 1. The D band in the Raman spectrum around 1350 cm⁻¹ is related to the defect levels in graphene, e.g. domain edges, and can be used as a measure of the material quality. The D peak is low in intensity compared to the other peaks, particularly in Fig. 1. The growth parameters for graphene by CVD were optimized by changing the temperatures (400, 500, 600 and 700°C) during the growth period (T_{growth}).

The characterization results of the Raman spectroscopy are presented in Table 1. The highest G to 2D ratio is 0.45 at T_{growth} of 600°C under hydrogen gas flow rate of 50 sccm, while the higher and lower G to 2D ratios were different.

Table 1

The values of Raman spectra characterisation in relation to G and 2D position, the ratio intensity between the two and full width at half maximum (FWHM) [22, 23, 44–48].

T_{growth} (°C)	Position G (cm^{-1})	position 2D (cm^{-1})	$I_{\text{G}}/I_{\text{2D}}$	$2D_{\text{FWHM}}$ (cm^{-1})	n GL~
400	1579.66	2706	2.14	77.8	3
500	1582.66	2709.89	3.04	79.68	4
600	1587.15	2676.11	0.45	49.42	1
700	1581.16	2713.78	1.94	73.64	2

The Raman spectra and mapping of multilayer graphene produced by chemical vapor deposition (CVD) are usually characterized by identifying layers of graphene on copper foil before their transferring into a target of substrate. The Raman spectrometer shown in Fig. 1 clearly displays G and 2D bands at approximately 1587.15 cm^{-1} and 2676.11 cm^{-1} , respectively. The highest full width at half maximum (FWHM) of the 2D band is 49.42 cm^{-1} for high quality graphene layers grown at 600°C with hydrogen flow of 50 sccm. The ratio of the relative intensity of the G band to the 2D band is 0.5 in these growth conditions, suggesting the existence of few graphene layers [45]. Additionally, the D band at approximately 1350 cm^{-1} in the Raman spectra is associated with defect levels in graphene, which may be used as an indicator of the graphene films quality. This band is less intense compared to other features. The ratio of intensity for the D and G bands is about 0.45, for a standard multilayer graphene obtained from CVD showing defects such as boundaries of domain [28, 49]. The boundaries of domain in the graphene sheet may also be characterized by the D band. The requirement of activation energy for benzene molecules dehydrogenation of PMMA-chlorobenzene is a low value on the copper (111) surface, approximately 1.47 eV, for the formation of graphene domains [29, 50–53]. Furthermore, using benzene as a carbon source for graphene layer production does not yield extensive graphene domains or continuous graphene films due to its low activation energy [5, 16]. This energy is enough to cause the necessary temperature increase (600°C) for the formation of the graphene layers by the adsorption and dehydrogenation of benzene molecules and the formation of C-C bonds. Also thermally unstable derivatives of chlorobenzene are formed at 500°C in hydrogen atmosphere [30, 54]. The concentration of H_2 flow has important influence on the growth rate of graphene and the number of graphene layers [31, 32, 55–58]. This effect is due to the role of T_{growth} in the thermodynamic nucleation process for graphene synthesis. In addition, it is of great importance for the treatment and evaluation of graphene domain size [33]. The number of graphene layers increases with increasing temperature of 700°C. The quality and quantity of the graphene layers increased with increasing growth temperature up to 600°C.

These observations provide interesting insights into the control and improvement of graphene growth rate by T_{growth} .

The Raman mapping of graphene synthesized on copper foil at 600°C with hydrogen flow of 50 sccm for 40×40 μm area is shown in Fig. 2 to fully characterize the graphene film quality. The Raman mapping is represented by the G/2D ratio, which can be useful to determine the layers number and the overall of the graphene film quality [34, 59]. This mapping shows micro-sized multilayer graphene flakes present in the optical image which was used for scanning analysis. One of these layers is always present in a region. However, the region size is much smaller than the other regions on copper foil. Mapping of the G/2D ratio indicates that about 60% of the graphene film on copper foil is multilayers. Moreover, due to the abundant carbon source in the CVD system, the graphene sheet has amorphous carbon. Oxide leakage into the reaction chamber, contamination of the surface catalyst and excess carbon supply during graphene growth may decrease the possibility of obtaining a monolayer and negatively affect the film quality [17, 33, 60, 61].

Graphene layers were placed onto a copper grid, etched from copper foil. Transmission electron microscopy (TEM) has been used for image the suspended layers of graphene on the grid. This method can be used to analyze the graphene structure and gives a clear insight into the carbon atoms composing the formation of the graphene layers. Figure 3. TEM image of the layer of graphene at 200 kV. The TEM image shows the strong contrast of carbon atoms in over-focus and the weak contrast of carbon atoms in under-focus as shown in Figure 3a. The mechanical transfer technique usually leads to topological defects on the surface of graphene layers. Also the mechanical support is not completely separated from the graphene layers on PMMA. These defects and the residual PMMA affect negatively the properties of graphene as an atomic layer [35, 62]. The TEM image (atomic resolution of 2 nm) illustrates the honeycomb structure of graphene consistent with the atomic carbon configuration of a single layer. However, there is a large amount of amorphous carbon around the hexagonal flake. The edges of the graphene flakes are mainly armchair type [37, 63]. Figure 3b shows the atomic structure of graphene obtained by electron diffraction (ED) during the TEM investigation. Additionally, the electron diffraction pattern obtained from the JOEL 2100 TEM shows that the six atoms of carbon are arranged in a hexagonal pattern, clearly showing the six-fold symmetry expected for graphene [38]. The position of the diffraction pattern can be indexed by the Miller-Bravais (hkil) indices. Moreover, the nanoscale electron diffraction pattern with different incidence angles of the graphene sheet and electron beam, can visualize the layers of suspended graphene. The electron diffraction in the TEM analysis confirms the graphene sheet is a monolayer as seen in Figure 3b. The black area in the image of TEM was caused by the aperture of objective which is intended to detect only scattering electrons at a small angle.

The evolution of the electrical structure in the carbon layer with growth as shown in the NEXAFS data is illustrated in Fig. 4. The NEXAFS spectra reveal the characteristic density of states (DOS) of graphene above the Fermi level [30] and the unique architecture of graphene: the π^* resonance shows up as the first prominent peak. The C K-edge NEXAFS peak assignments of the four growth conditions are also summarized in Fig. 4 and Table 2. The π^* resonance peak at 285.5 eV is weak in graphene, generally due

to its planar structure, which theoretically forbids the excitation by an in-plane polarized X-ray beam. The extra C K-edge peaks (π^* and σ^*) at 287 to 290 eV correspond to different functional groups attached to the graphene atomic layer, typically to defect sites [61, 64]. The last two peaks are carbon-carbon bonds, which are the σ^* resonances in the graphene structure and can be easily excited by the laser with in-plane polarization. The NEXAFS spectra show that the graphene synthesized at different temperatures have different features in terms of defects, carboxyl groups, C–H and C–OH bonds and C–C bonding. The intensities and sharpness of the characteristic $\pi^*_{C=C}$ and σ^*_{C-C} peaks increase with the growth temperature, indicating improved graphene quality and reduced defect density. These results highlight the important role of the control temperature during the process of synthesis to improve the electrical structure and the purity of the graphene.

Table 2

The main NEXAFS features and their proposed assignments are listed in the Table [31, 32].

Bond	Peak energy (eV)	Assignments
C = O	284	Defects
C = C	285.5	π^* resonance
C-H, C-OH	287.8	σ^* resonances
O-C = O	288.4	π^* (carboxyl)
C-C	291.8	σ^* resonances
C-C	292.4	σ^* resonances

The graphene quality was defined by the carbon atoms arrangement, preferably in a monolayer in a lattice of planar hexagonal. Once graphene is fabricated, it has high potential for applications in electrical and optoelectronic devices. The thickness of the graphene layer is about 1 nm, the surface shape and thickness of which could be measured via atomic force microscopy (AFM), as illustrate in Fig. 5. Some defects are visibly elevated above the substrate, possibly due to contamination from the PMMA utilized for mechanically supporting the sheet of graphene through the process transfer.

Conclusion

In the present study, we demonstrate the significant growth of graphene layers on copper foil by low temperature chemical vapour deposition (CVD). The quality of graphene sheet was improved by varying the hydrogen flow rate and the results were different at different flow rates. The decomposition temperature of the carbon source, PMMA-chlorobenzene, is significantly different from that of bulk pure PMMA or chlorobenzene solvent. The PMMA-chlorobenzene precursor was successfully utilized to grow graphene multi-layer on copper foil. The growth of low temperature at around 600°C is a possible source for thermal energy that can break the bonds of the carbon source. The energy is the activation energy for the carbon atoms deposition on the surface of catalyst. Domains graphene are honeycomb like

structures surrounding via the carbon amorphous. Increasing of these domains increases the chemical bonding in the graphene film. The graphene films exhibited uniform layers with small domain size. This carbon source was effective in reducing the required breakdown temperature for formation of graphene layers. In conclusion, NEXAFS spectra for the increased graphene growth temperature from 400°C to 700°C show an increased order of the structure and a higher density of defect sites. This trend is further supported by the increased intensity and clarity of the $\pi^*_{C=C}$ resonance as well as the decrease in the characteristics corresponding to the oxygen containing groups. The results show that higher synthesis temperatures lead to higher quality graphene with less defects and less functionalization, both important for improving the electrical and chemical properties of graphene.

Declarations

Author Contribution

ALAA Y ALI, corresponding author; writing the main draft of the paper, analysis data, supervision Ahmed Ibrahim Farhan; resources , methodology Sundus Alzuhairi; methodology Mustafa Y. Ali; software , resources

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Figures

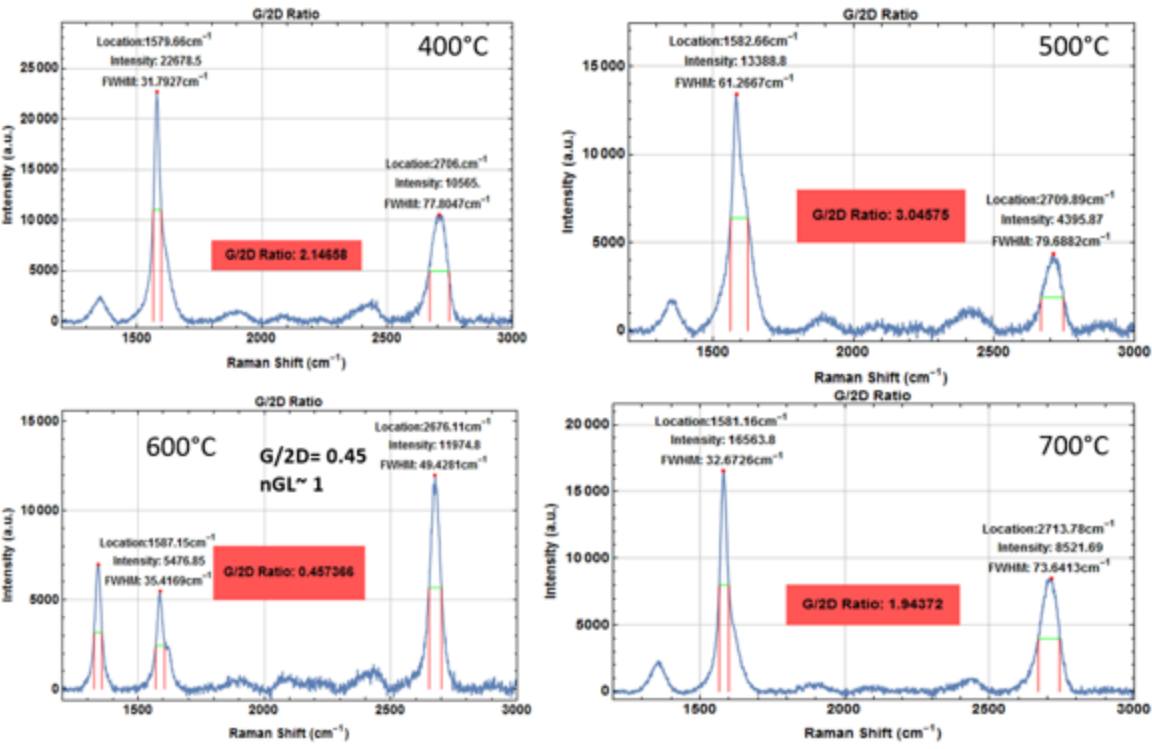


Figure 1

The spectrum of Raman for the thin films of graphene was growth at different temperatures.

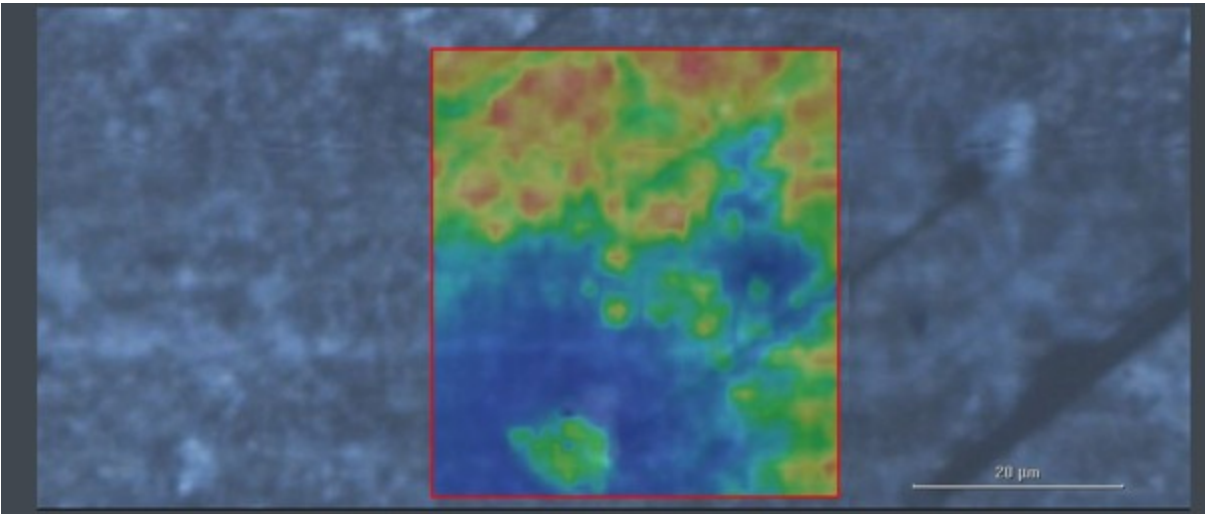


Figure 2

Presents the Raman mapping of G/2D ratio for graphene layer at 600°C with 50 sccm of hydrogen flow rate.

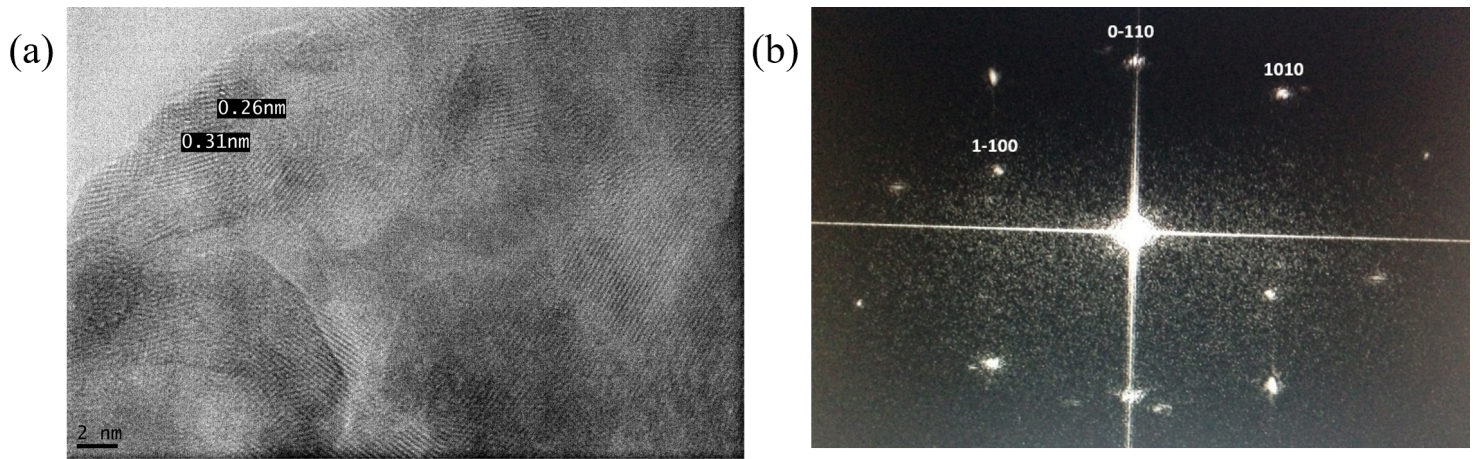


Figure 3

(a) Image of Transmission electron microscopy (TEM) for layers of graphene suspended on copper grid and (b) the pattern diffraction for atoms of carbon using a JOEL 2100 TEM.

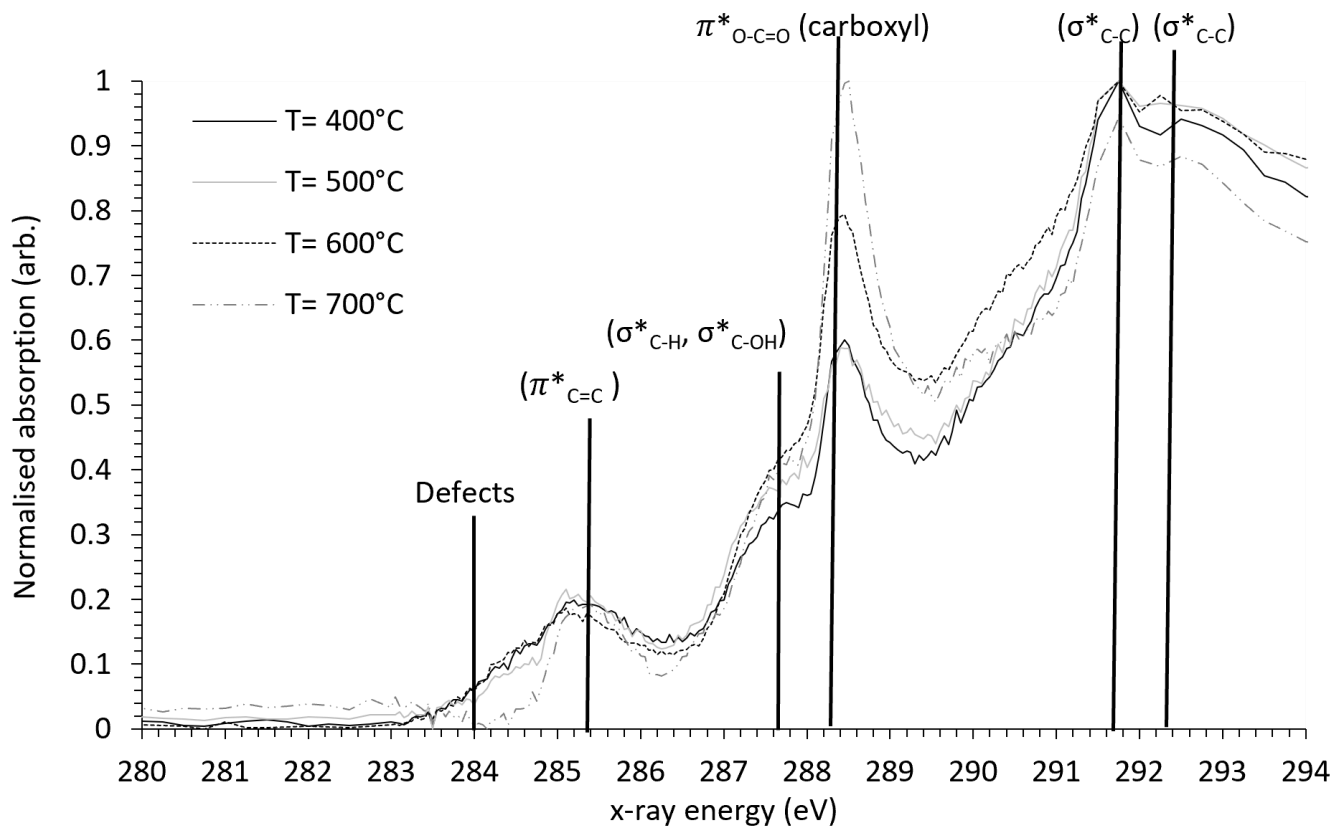


Figure 4

Shows the NEXAFS spectra of graphene grown at different growth temperatures (T_{growth}). The synthesis was carried out at H_2 flow rate of 50 sccm with copper foil catalyst annealed at 900°C for one hour. The

photoabsorption spectra at the C K-edge are shown.

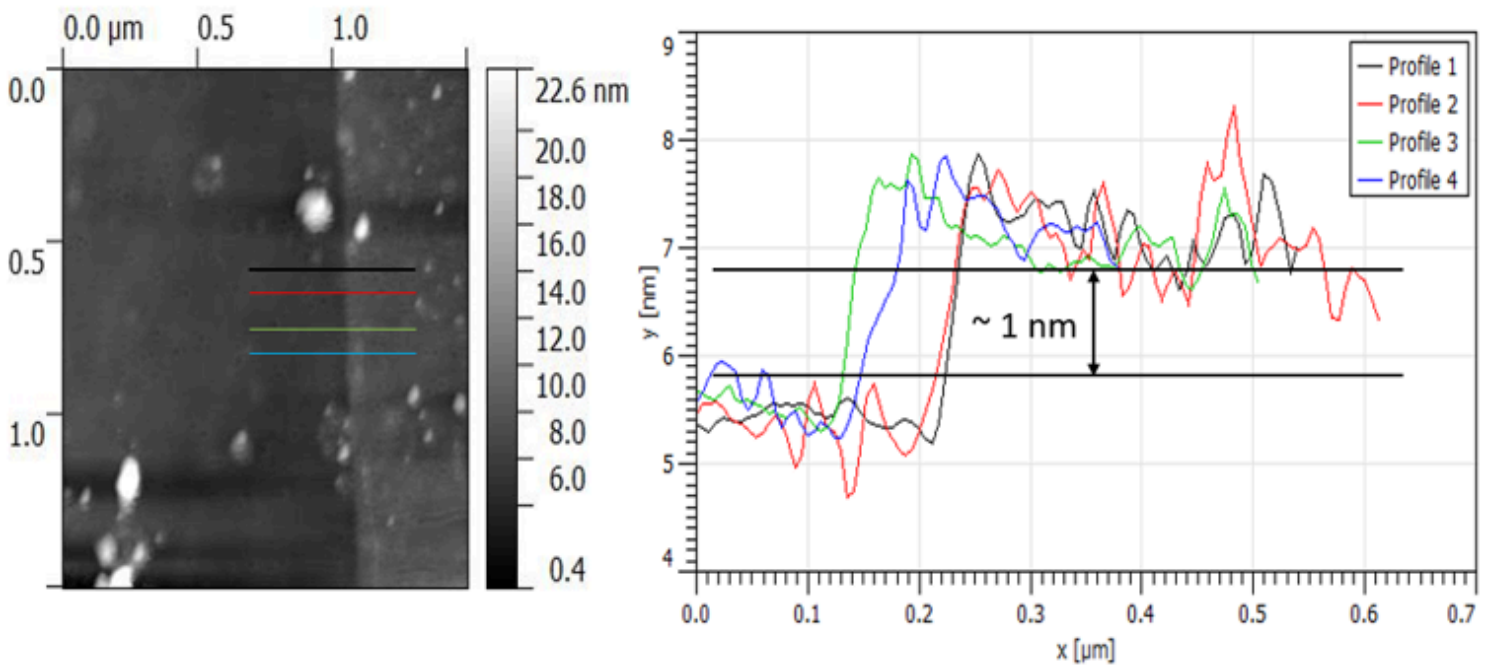


Figure 5

Image of AFM for layer graphene on silicon substrate growth at 600°C with 50 sccm of flow rate hydrogen.

Supplementary Files

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