

# **Review on Large-Area Synthesis of some Graphene Films, Characterizations and Applications.**

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## **ABSTRACT**

For two decades and beyond, remarkable progress has been made in the use of chemical vapour deposition methods for comprehending 2D materials growth. This review is aimed at providing an overview of several synthesis, characterizations and applications of large area graphene film on some substrates. First, the major growth methods are explained. Next, the mechanism of the graphene growth is discussed, focusing on reaction of precursors, diffusion of adatoms, energetics and kinetics of growth fronts, and effects of substrates. Then, the advantage of growing graphene film on some substrate over another is explained in some of the synthesis. Furthermore, the characterization of the various synthesized graphene films are explained, which suggests a suitable application to it.

**Keywords:** chemical vapour deposition, 2D materials, precursors, graphene-growth, substrate, application

## **INTRODUCTION**

Recently, much attention has turned to the structural and electronic properties of carbon-based materials. At present, graphene is the hottest topics in condensed-matter physics and materials science. This is because graphene has not only unusual properties regarding extreme mechanical strength, thermal conductivity and 2-dimensional films, but also peculiar electronic characteristics such as Dirac-particles with a linear dispersion, transport energy gap and simply absorption coefficient of lights (*Geim & Novoselov, 2007; Nair et al., 2008*). These unique properties mean it could have a wide array of practical uses. In addition to monolayer graphene,

few-layer graphene has been extensively studied. For example, bi-layer graphene creates a band gap when an external electric field is applied (*Castro et al., 2007; Zhang et al., 2009*). Graphene sheets have been produced mainly by exfoliating graphene flakes from bulk graphite and depositing them on the SiO<sub>2</sub>/Si substrate. However, the size and crystalline quality are not easily controlled. Some groups have grown epitaxially graphene sheets on SiC(0001) (*Hibino et al., 2010*), however the graphene layers have been widely distributed in thickness. (*n. g. prikhod'ko et al. 2014*)

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice. It is a 2D material with outstanding physical properties. The successful isolation of graphene has drawn great interest for experimental investigations and has opened the route for a wide range of potential applications. Mechanically exfoliated graphene from bulk graphite has enabled fundamental investigations on the physical properties of graphene; however, this technique is not suitable for the integration in practical device fabrication processes nor for the synthesis of large surface area devices. For several applications, if one excludes active semiconducting devices exploiting the quantum properties of single carbon layers, a material composed of a few layers graphene (FLG) is also extremely promising. The overall characteristics of graphene films, both single and FLG, such as size, crystallinity, continuity, homogeneity and fabrication reproducibility are mandatory for successful practical application. (*Keun Soo Kim et al. 2009*). Here we reviewed some methods which some graphene films are synthesized in large area, its characterizations and some of its applications. The result obtained from the characterizations will also reveal a new application of graphene in the future, and will serve as bases for the study and discovery of future graphene synthesis and application.

## **SYNTHESIS METHODS**

### **Synthesis of Graphene Films in a Flame**

In this method, the temperature of 900–950°C and exposure time of 5 min are demonstrated to be suitable for the synthesis of graphene films on a nickel substrate, which is preferable to a copper substrate. It is indicated that the formation of graphene layers on the substrate occurs vertically along the flame height, with subsequent changeover to a soot structure. It is displayed that the minimum number of graphene layers (two or three) is observed at angles of inclination of the substrate relative to the vertical axis of the flame within 0°–30°. (*n. g. prikhod'ko et al. 2014*)

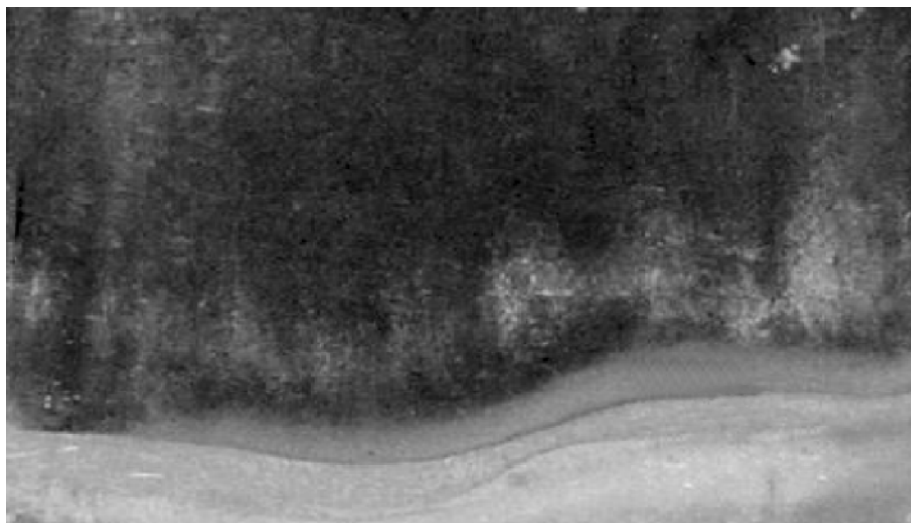


Fig 1. Photograph of a nickel substrate with carbon structure.

The Ni surface is the excellent substrate for growth of single-layer-graphene sheet with macroscopic dimensions. Graphene sheets with a  $1 \times 1$  atomic structure grew up epitaxially by Chemical vapour deposition (CVD) or surface segregation techniques. It was observed that the graphene growth of mono-, bi- and tri-layer step by step using carbon segregation phenomena on Ni by Low-energy electron microscopy (LEEM). The summaries are as follows;

1. One can grow the uniform monolayer graphene on Ni by adjusting the temperature. No domain boundaries and wrinkles were detected by LEEM.
2. The second- and the third-layer graphene grew at the interface under the first and the second layers. Bi-layer graphene domains grew at least  $100\mu\text{m}$  scale. The third-layer started to grow before the completion of second-layer at 1050K in this experiment. More precise control of temperature seems to be required to complete the second-layer before starting the third-layer growth.
3. Shape of the islands differed depending on the thickness; the first- and third layer islands exhibit hexagonal edges, while the second-layer islands possess dendritic edges.
4. The different shapes of the first, second and third-layer islands presumably originate from the interfacial-bond strength depending on the graphene thickness.
5. The number of nucleation sites of graphene growth is extremely small on Ni surface, which is an important factor for growth of large single-domain graphene crystals.
6. Chemical etching of Ni substrate made it possible to separate macroscopic self standing graphene sheets.

### **Synthesis of Graphene Films on Copper Substrates by CVD of Different Precursors:**

Graphene films of the order of  $1\text{cm}^2$  were grown on copper foil substrates by CVD using hydrogen/methane or hydrogen/argon/ethanol mixtures as gas precursors. The growth processes

were performed near  $1,000^{\circ}\text{C}$  both at atmospheric and low pressures. A system for the fast cooling of the sample, based on the fast extraction from the hot zone of the furnace, was implemented allowing for rapid decrease of the temperature below  $600^{\circ}\text{C}$  in few seconds. Samples grown under different conditions were analyzed by scanning electron microscope (SEM), Raman spectroscopy and X-ray photoelectron spectroscopy (XPS) with the aim to assess their characteristics and to refine the growth process. (R. Giorgi et al).

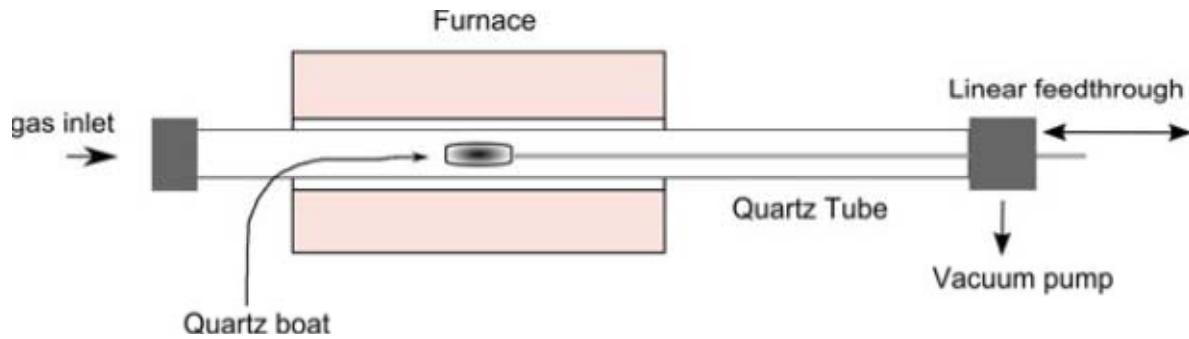


Fig 2. Scheme of the CVD reactor

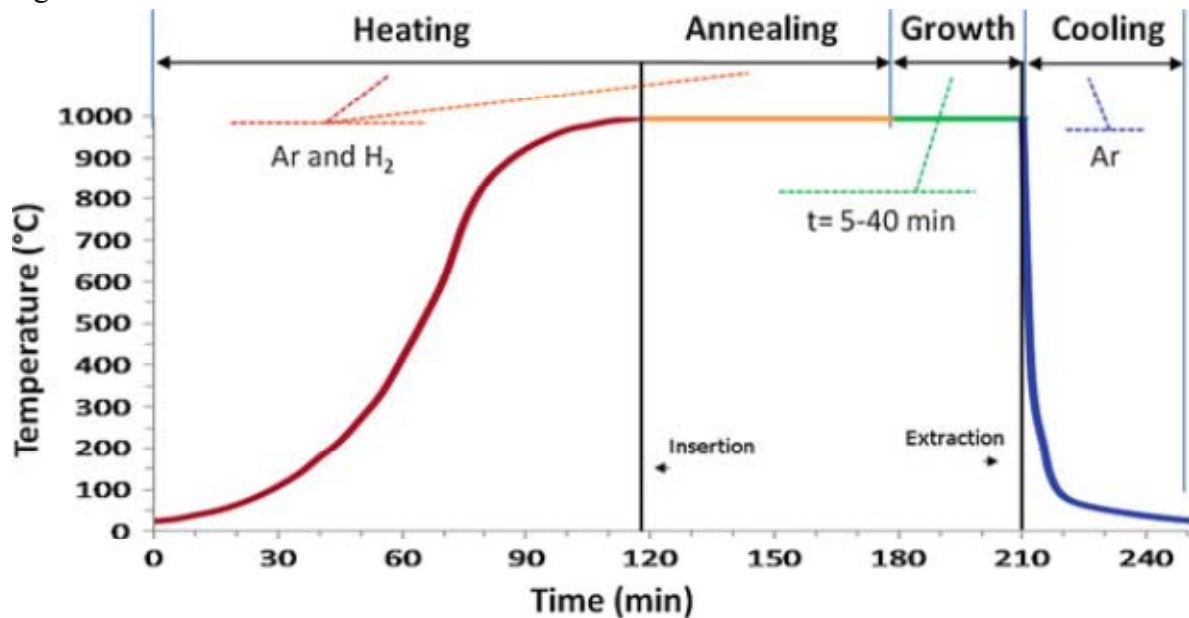


Fig 3. Graphene growth process

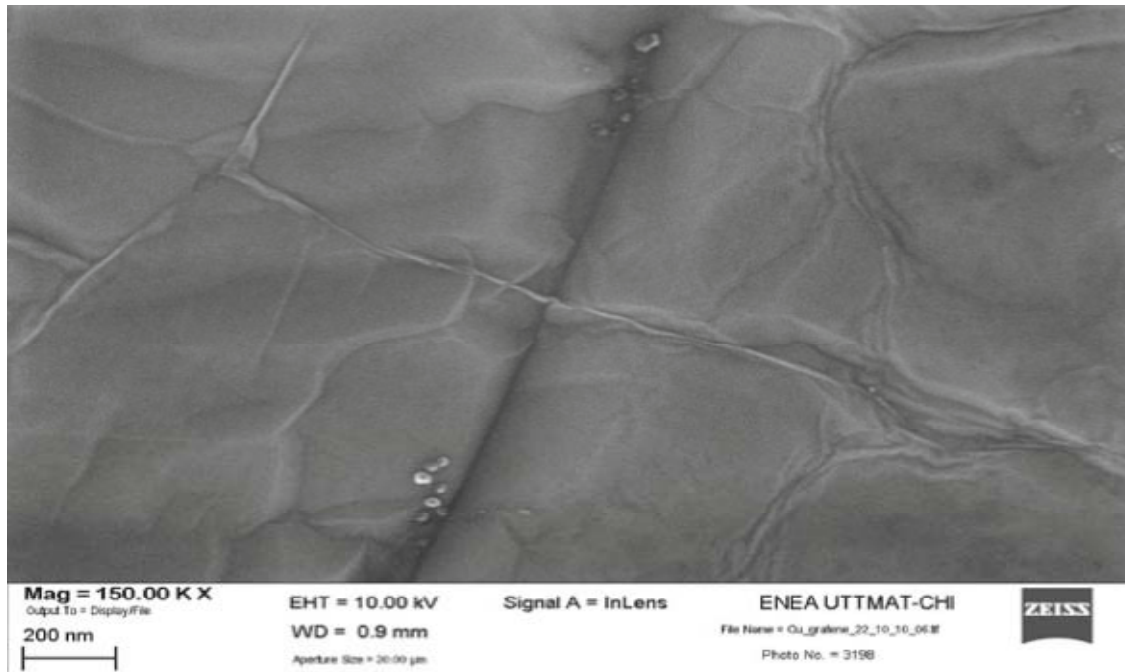


Fig 4. SEM image of Cu substrate after graphene growth

Films consisting of less than 5 graphene layers have been grown by CVD both from methane and ethanol as precursors. The use of copper substrates has allowed the growth of large area continuous films of the order of  $1\text{cm}^2$ ; a wet procedure was followed for the transfer of the graphene films on to  $\text{SiO}_2/\text{Si}$  substrates more suitable for their characterization. Pressure and growth time have been found to be the main process parameters affecting the thickness and the quality of the graphene films. The grown films exhibited good crystallinity, but result composed of different overlapping regions with different number of layer. Factors influencing the film homogeneity and uniformity have been identified in the substrate features. Future work will be focused on the optimization of substrate treatments, with the aim to achieve more uniform large area graphene films with controlled structure: number of layers and crystallinity. The matching of the large copper grain size (upto 1mm) with controlled growth of graphene (single and FLG) remains an interesting goal and a high challenge. (Keun Soo Kim *et al.* 2009)

### **Large-Area Synthesis of Graphene Films on Copper Foils:**

The large-area graphene films of centimeters on copper substrates was grown by chemical vapor deposition by using methane. The films are predominantly single layer graphene with a small percentage (less than 5%) of the area having few layers, and are continuous across copper surface steps and grain boundaries. The low solubility of carbon in copper appears to help make this growth process self-limiting. Graphene film transfer processes were also developed to arbitrary substrates, and dual-gated field-effect transistors fabricated on  $\text{Si}/\text{SiO}_2$  substrates

showed electron mobilities as high as  $4050 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$  at room temperature. (Xuesong Li et al, 2009)

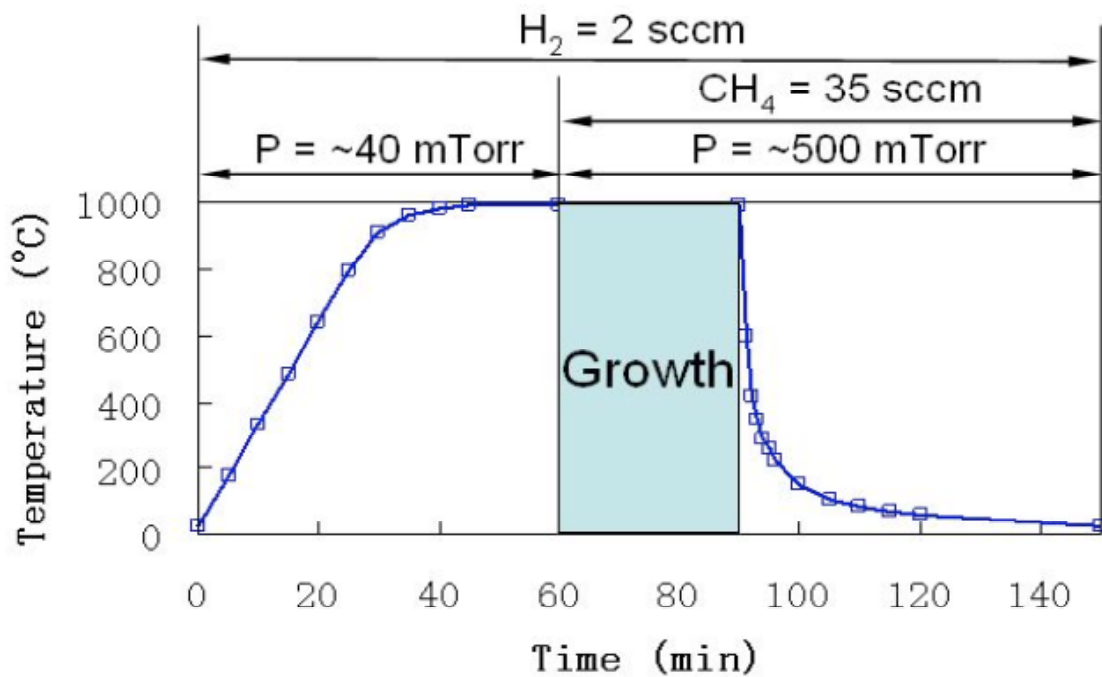


Fig 5. Time dependence of experimental parameters: temperature, pressure, and gas composition/flow rate.

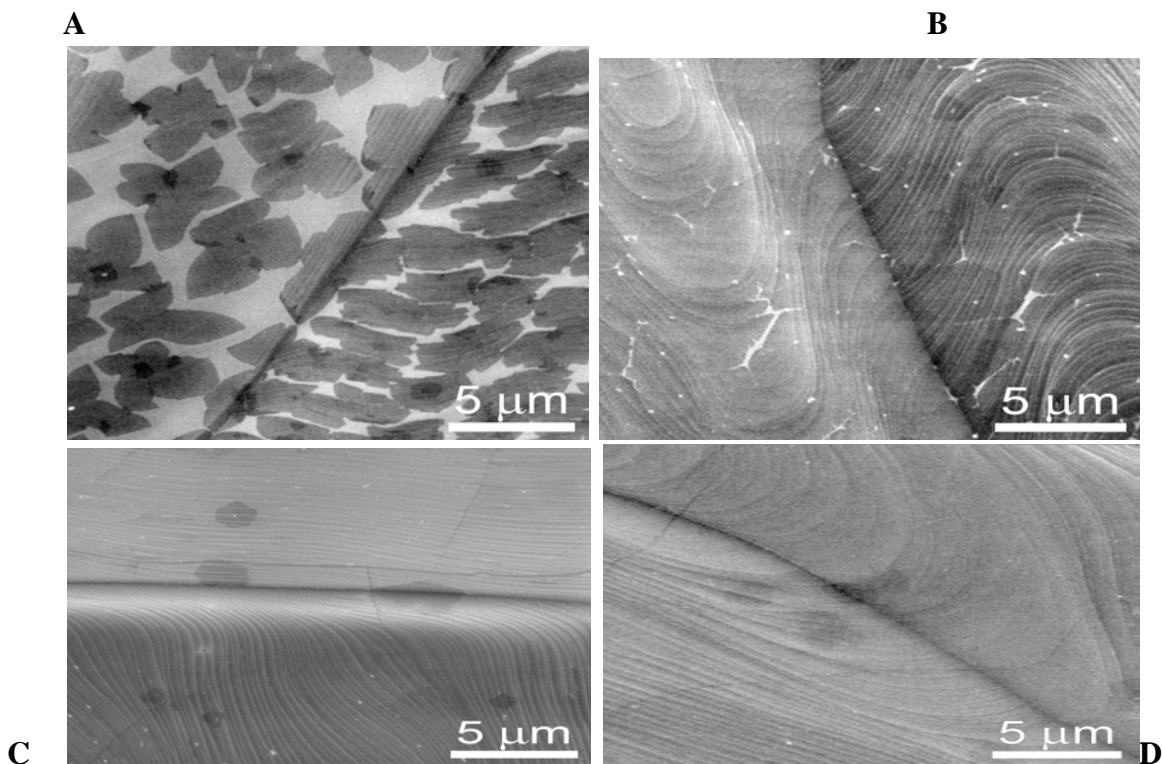


Fig 6. SEM images of graphene on Cu with different growth times of (A) 1 min, (B)

2.5 min, (C) 10 min, and (D) 60 min, respectively.

In recent work, thin Ni films and a fast-cooling process have been used to suppress the amount of precipitated C. However, this process still yields films with a wide range of graphene layer thicknesses, from one to a few tens of layers and with defects associated with fast cooling (*R. Giorgi et al, 2014*). Our results suggest that the graphene growth process is not one of C precipitation but rather a CVD process. The precise mechanism will require additional experiments to understand in full, but very low C solubility in Cu (*Lei Liu et al, 2009*), and poor C saturation as a result of graphene surface coverage may be playing a role in limiting or preventing the precipitation process altogether at high temperature, similar to the case of impeding of carburization of Ni (*Whi Dong Kim et al, 2011*). This provides a pathway for growing self-limited graphene films. To evaluate the electrical quality of the synthesized graphene, we fabricated dual-gated FET with Al<sub>2</sub>O<sub>3</sub> as the gate dielectric and measured them at room temperature. Along with a device model that incorporates a finite density at the Dirac point, the dielectric, and the quantum capacitances (*F. K. Perkins 2013*), the data are shown in Fig. 3. The extracted carrier mobility for this device is  $\sim 4050 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ , with the residual carrier concentration at the Dirac point of  $n_0=3.2\times 10^{11} \text{ cm}^{-2}$ . These data suggest that the films are of reasonable quality, at least sufficient to continue improving the growth process to achieve a material quality equivalent to the exfoliated natural graphite. (*Xuesong Li et al 2009*)

### **Synthesis of multi-layer graphene films on copper tape by atmospheric pressure chemical vapor deposition method:**

Graphene films were successfully synthesized by atmospheric pressure chemical vapor deposition (APCVD) method. Methane (CH<sub>4</sub>) gas and copper (Cu) tapes were used as a carbon source and a catalyst, respectively. The CVD temperature and time were in the range of 800–1000°C and 10s to 45min, respectively. The role of the CVD temperature and time on the growth of graphene films was investigated in detail via scanning electron microscopy (SEM) and Raman spectroscopy techniques. The results of SEM images and Raman spectra show that the quality of the graphene films was improved with increasing of CVD temperature due to the increase of catalytic activity.

Multilayer graphene films were successfully synthesized on the Cu tapes by APCVD method. The quality of the graphene films was improved with increasing CVD temperature. The growth time does not much affect the number of layers of graphene films. CVD temperature of 1000°C and CVD time of 30min are the optimum temperature and time for growing high-quality graphene films on the Cu tape, respectively. The graphene films were successfully transferred from the Cu tape to other substrates by wet etching Cu with a solution of iron(III) nitrate. (*Van Tu Nguyen1. 2013*)

## Self-Standing Graphene Sheets Prepared with Chemical Vapor Deposition and Chemical Etching:

The growth mechanism of graphene layers on Ni surface was studied. The in-situ observation of the graphene growth of mono-, bi- and tri-layers using carbon segregation phenomena on Ni by low energy electron microscopy (LEEM) were reported, which is a powerful technique to investigate thin films in mesoscopic scale. We also fabricated the self-standing graphene sheets by chemically etching the substrate (*Odahara et al., 2009*). The chemical process to remove the Ni substrate makes it possible to prepare a self-standing graphene sheets, which are characterized by scanning electron microscopy (SEM) or transmission electron microscopy (TEM).

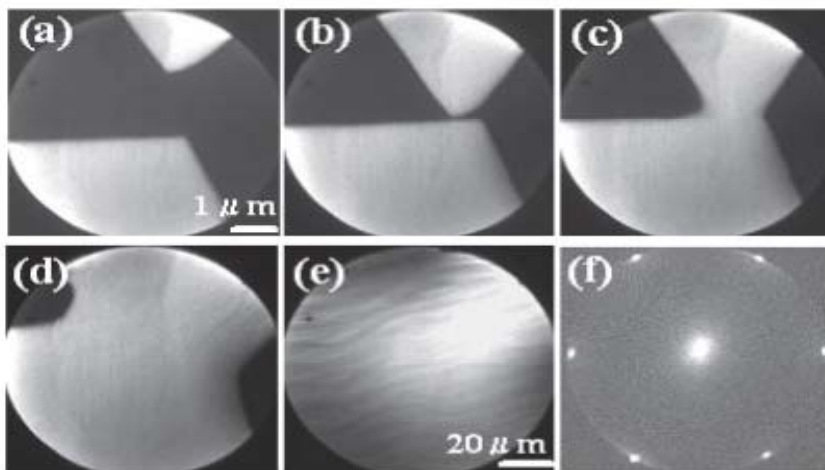


Fig 7. Typical snapshots of LEEM images obtained as the temperature was decreased from 1200 K to 1125 K (images (a) to (d)). The observed area was  $6\mu\text{m}$  field-of-view. Letter in each image indicates the time-lapse order. Two graphene domains were united to form one graphene sheet. Image (e) is a typical LEEM image of  $100\mu\text{m}$  field-of-view. The surface was entirely covered with monolayer graphene. LEEM images were obtained at the primary electron energy of 3.5 eV. Image (f) is a typical LEED pattern observed in the graphene covered surface. The orientation of the graphene was slightly altered because the sheet is curved.



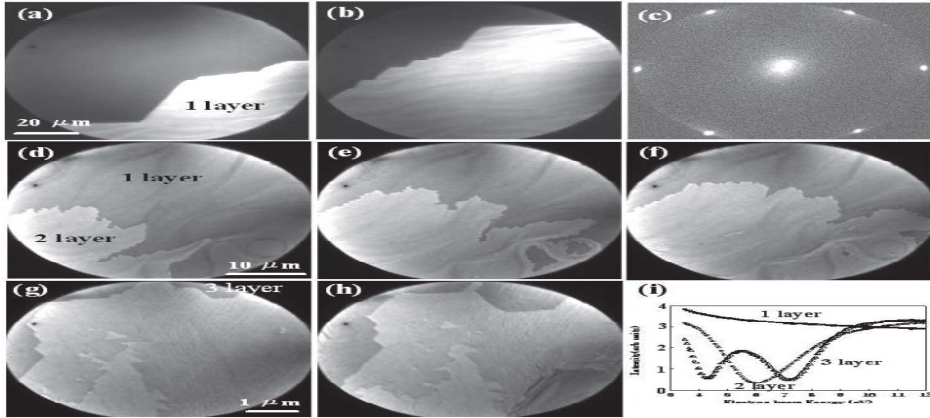


Fig 8. Typical LEEM images of the graphene growth at different stages: (a)-(b) the first layer growth observed at 1125K, (d)-(f) the second layer at 1050K and (g)-(h) the third layer at 1050K. Image (c) is a typical  $\mu$ LEED pattern of a 1 x 1 atomic structure obtained from the single-layer graphene-covered surface. Image (i) is the electron reflectivity-energy curves obtained from each area. Image (e) is a growth stage that followed after stage (d) before stage (f).

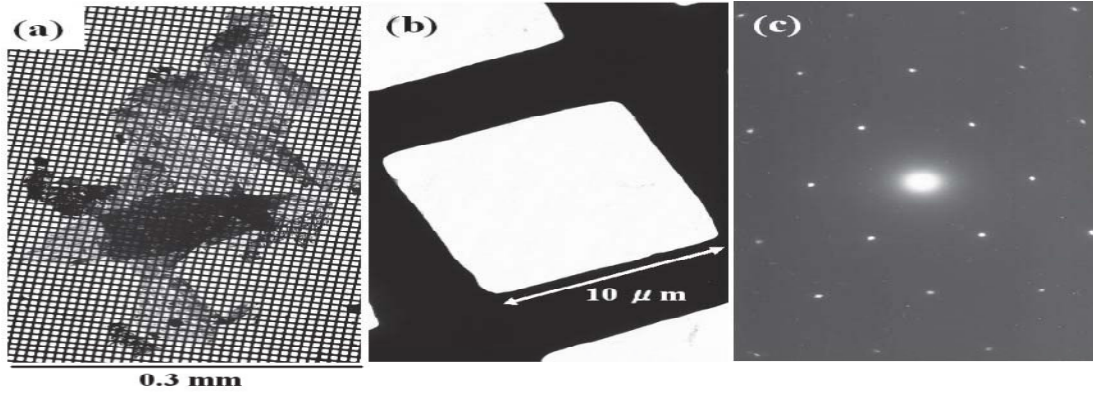


Fig 9.

- (a) A TEM image of a carbon aggregate on the Au mesh with squares  $10 \mu\text{m} \times 10 \mu\text{m}$  in area, (b) A magnified TEM image of the thinnest area of the carbon aggregate, and (c) its electron diffraction pattern.

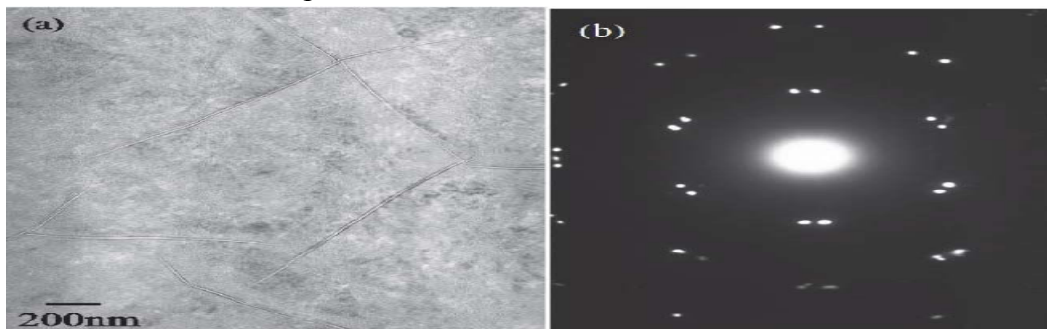


Fig 10. A TEM image of the other area in the carbon aggregate (a) and its diffraction pattern (b). One can see clearly doublets of diffraction spots in (b), and new carbon-nano-tube like structures in (a). The hole was covered with double-layer graphene.

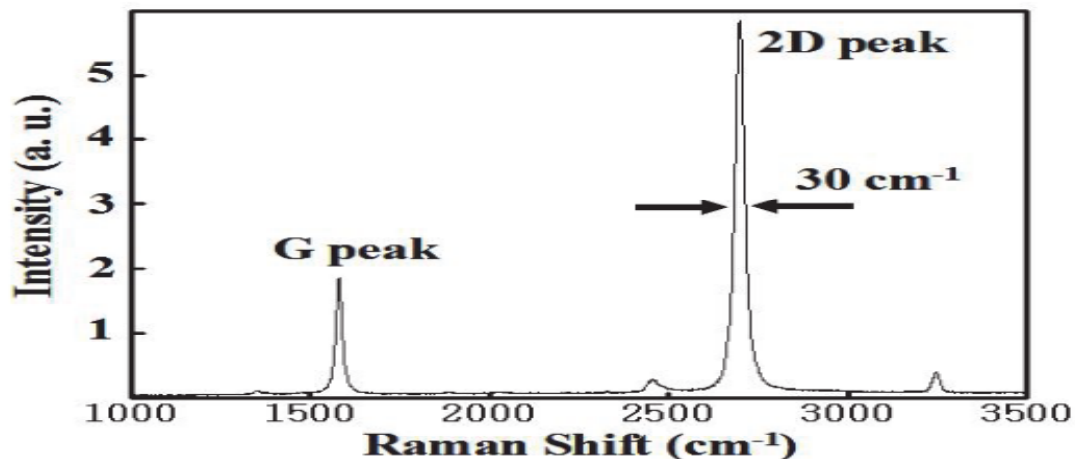


Fig 11. Typical Raman spectrum of the monolayer self-standing graphene sheets. Small defect-origin D peak was detected at  $\sim 1350$   $\text{cm}^{-1}$ .

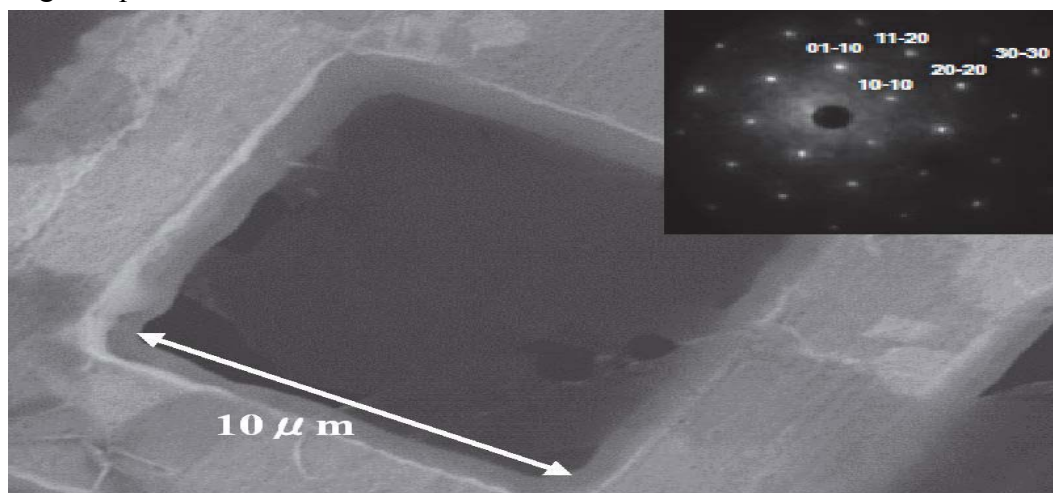


Fig 12. The SEM image of single graphene sheet at 5 kV and its LETED pattern (upper right).

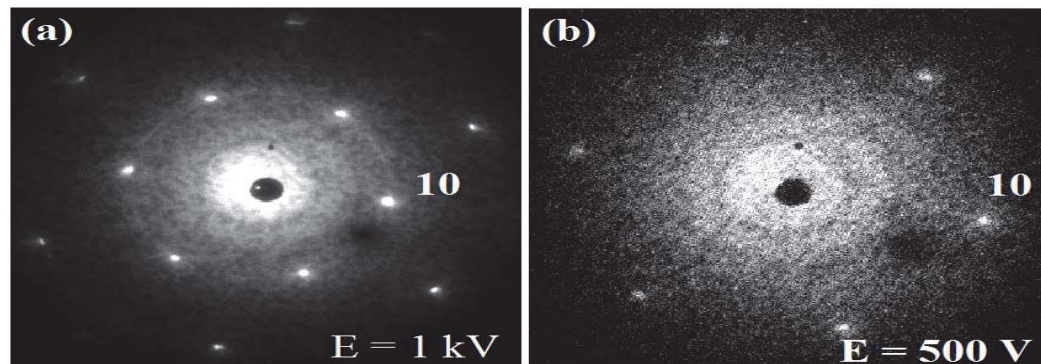


Fig 13. The LETED pattern of single-layer graphene at (a) 1 kV and (b) 500 V.

LETED stands for (Low Energy Transmission Electron Diffraction)

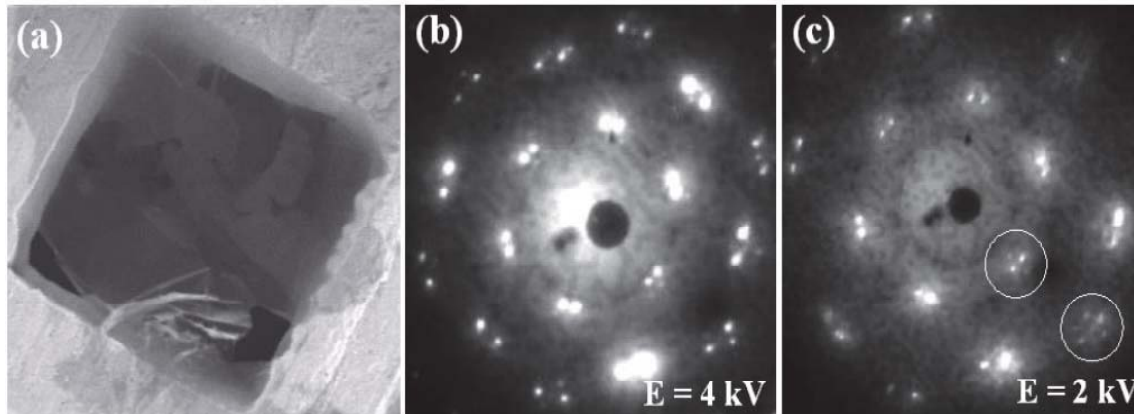


Fig 14. The SEM image of folding double graphene sheet (a) and its LETED pattern at (b) 4 kV and (c) 2kV.

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## Applications of large scale graphene

### Graphene for nanoelectronics

Graphene shows a glaring ambipolar electric field effect whereby charge carriers can be tuned continuously between electrons to holes. Single layer graphene atop a thermally grown  $\text{SiO}_2$

layer on a highly doped Si substrate may serve as a prototype of a field effect transistor. Under this arrangement, SiO<sub>2</sub> play the role of an insulating layer, so a back-gate voltage can be applied to vary carrier concentration. Early graphene FET devices demonstrated by Novoselov exhibited dopant concentrations as high as 10<sup>13</sup> cm<sup>-2</sup> and achieved a mobility that could exceed 10,000 cm<sup>2</sup> /Vs (Novoselov, Geim et al. 2004). This translates into ballistic transport on submicron scales. The room-temperature mobility is limited by impurities or corrugations of the graphene surface, which means that it can still be improved significantly up to the order of 10<sup>5</sup> cm<sup>2</sup> /Vs (Bolotin, Sikes et al. 2008; Du, Skachko et al. 2008).

Electrons present in graphene act like mass-less comparable particles controlling a majority of its electronic properties. Among the most important results of such uncommon diffusion relation can be seen in the case of half-integer “Quantum Hall Effect” and the unavailability of localization, which can be very essential for graphene-based field effect transistors, (FET), (Geim and Novoselov 2007). Mechanical exfoliation of highly ordered pyrolytic graphite (HOPG) or high purity graphite flakes can lead to the generation of graphene crystals with very few flaws, which in turn show high movability of the charge carriers. Figure 12 shows scanning electron microscopy (SEM) and atomic force microscopy (AFM) of the graphene based device reported in the literature as having the highest electron mobility to date (Bolotin, Sikes et al. 2008). The graphene film was obtained by mechanical exfoliation of graphite on Si/SiO<sub>2</sub> substrate in which the oxide layer below the graphene was etched in order to obtain a free-standing graphene flake connecting the metal electrodes.

Electrical measurements of resistivity vs. gate voltage show the intrinsic ambipolar characteristics of graphene. It was also established that the transfer characteristics of the device is greatly improved after undergoing a high-current annealing procedure to remove contaminants from the graphene surface. Mobility  $\mu$  for this device reaches an exceptional value of 230,000 cm<sup>2</sup>/Vs measured at the highest carrier density  $n = 2 \times 10^{11}$  cm<sup>-2</sup>. Such high mobility would in principle favor high frequency performance. Furthermore, graphene devices pursuing high frequency have demonstrated encouraging characteristics, exhibiting a cutoff frequency  $f_T$  of 26 GHz, which is the frequency at which the current gain becomes unity and signifies the highest frequency at which signals are propagated (Lin, Jenkins et al. 2008). Only recently, P. Avouris and collaborators reported the fabrication of graphene FETs on SiC substrates with cutoff frequency of 100 GHz for a device of gate length of 240 nm and using a source-drain voltage of 2.5 V (Lin, Dimitrakopoulos et al.). This  $f_T$  exceeds those previously reported for graphene FETs as well as those for Si metal-oxide semiconductor FETs for the same gate length (~40 GHz at 240 nm) (Meric, Baklitskaya et al. 2008; Moon, Curtis et al. 2009).

### **CVD graphene for macroelectronics: Transparent conductive films**

Another intrinsic property of graphene is its transparency. A single sheet of graphene absorbs only 2.3 % of the incident light. Such combination of high conductivity and low light absorption

makes this material an ideal candidate as a transparent conductive film. It is very tempting to use the unique properties of graphene for technology applications even beyond graphene FET applications. Composite materials, photo-detectors, support for biological samples in TEM, mode-lockers for ultrafast lasers and many more areas would gain strongly from using graphene for non-FET purposes. (*S. Goniszewski et al. 2014*)

## **Graphene applications in photovoltaics**

### **Photovoltaic cells: Graphene vs ITO**

Solar energy harvesting using organic photovoltaic (OPV) cells has been proposed as a means to achieve low-cost energy due to their ease of manufacture, light weight and compatibility with flexible substrates. A critical aspect of this type of optoelectronic device is the transparent conductive electrode through which light couples into the device. Conventional OPVs typically use transparent indium tin oxide (ITO) or fluorine doped tin oxide (FTO) as such electrodes (*Peumans, Yakimov et al. 2003*). However, the scarcity of indium reserves, intensive processing requirements, and highly brittle nature of metal oxides impose serious limitations on the use of these materials for applications where cost, physical conformation, and mechanical flexibility are important.

Graphene monolayer has a transparency of 97-98 percent and the sheet resistance of undoped graphene is of the order of  $\sim 6\text{k}\Omega$ ; for which graphene films are suitable for applications as transparent conductive electrodes where low sheet resistance and high optical transparency are essential (*Gomez De Arco, Zhang et al.*). Conventional methods to obtain graphene thin films such as epitaxial growth, micromechanical exfoliation of graphite and exfoliation of chemically oxidized graphite are either expensive, unscalable or yield graphene with limited conductivity due to a high defect density. However, chemical vapor deposition has surged as an important method to obtain high quality graphene films. In particular, films with sheet resistance of  $280\ \Omega/\text{sq}$  (80% transparent) and  $770\ \Omega/\text{sq}$  (90%transparent) have been reported in the literature for graphene synthesized on Ni films, while sheet resistance of  $350\ \Omega/\text{sq}$  (90% transparent) has been reported for CVD graphene on Cu films, which represents a good advance in the use of graphene as transparent conductive films. Another advantage of CVD is its scalability; we have reported wafer-scalesynthesis and transfer of single- and few-layer graphene for transistor and photovoltaic device fabrication (*Gomez De Arco, Zhang et al.; Gomez, Zhang et al. 2009*).

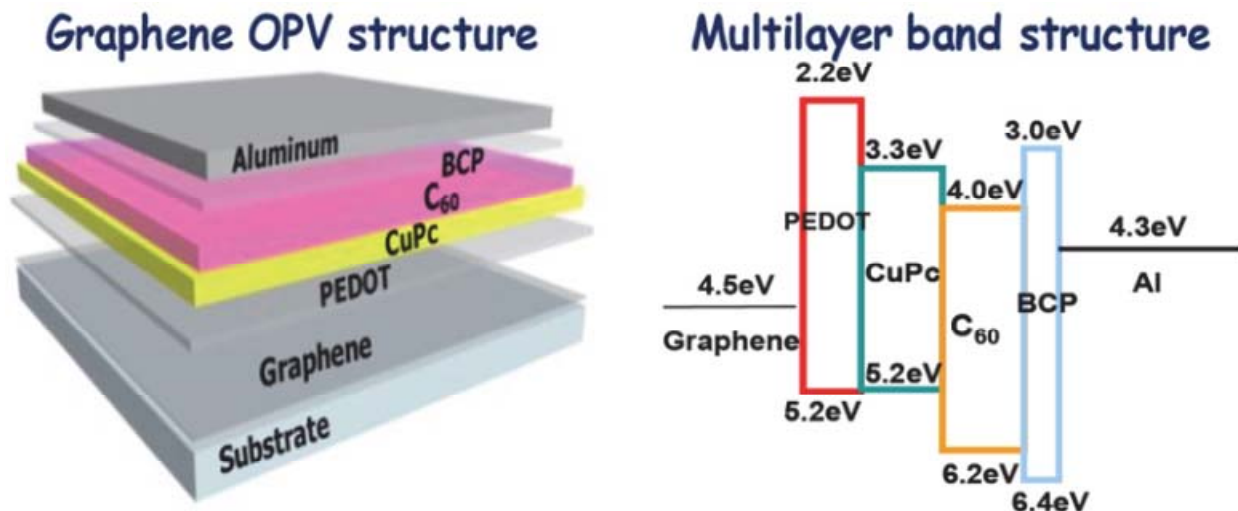


Fig 15. Schematic representation of the energy level alignment (right) and construction of the heterojunction organic solar cell fabricated with graphene as anodic electrode: CVD graphene / PEDOT / CuPc / C<sub>60</sub> / BCP / Al.

## SUMMARY AND CONCLUSION

The report reveals some detailed synthesis methods of large area graphene from different precursors, starting from the growth processes, the precise mechanisms with given optimized parameters, to yield some maximum graphene films with good properties. Results obtained from the characterization of the various synthesized graphene films confirmed that the properties of the films are of good quality, which makes them useful and can be employed for different applications.

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