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## Synthesis of Homogenous Bilayer Graphene on Industrial Cu Foil \*

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We synthesize the homogenous graphene films on cheap industrial Cu foils using low pressure chemical vapor deposition. The quality and the number of layers of graphene are characterized by Raman spectra. Through carefully tuning the growth parameters, we find that the growth temperature, hydrocarbon concentration and the growth time can substantially affect the growth of high-quality graphene. Both single and bilayer large size homogenous graphenes have been synthesized in optimized growth conditions. The growth of graphene on Cu surface is found to be self ceasing in the bilayer graphene process with the low solubility of carbon in Cu. Furthermore, we have optimized the transfer process, and clear graphene films almost free from impurity are successfully transferred onto Si/SiO<sub>2</sub> substrates. The field effect transistors of bilayer graphene are fabricated, which demonstrates a maximum hole (electron) mobility of 4300 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup> (1920 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup>) at room temperature.

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Two-dimensional graphene has exceptionally exhibited physical, chemical, optical and mechanical properties and has attracted wide research interests since its discovery in 2004.<sup>[1-6]</sup> Intrinsically the monolayer graphene is a semimetal with zero bandgap. Patterning nanometer-width graphene ribbons or utilizing special substrates can produce a sizeable energy bandgap.<sup>[7-11]</sup> An electric field controlled band up to 250 meV was observed in bilayer graphene.<sup>[12]</sup> Tunable on/off ratio up to 3000 at room temperature was achieved in bilayer graphene nanoribbons, which is crucial for its electronic applications.<sup>[13]</sup> Thus controlling the number of graphene layers is a very important issue in graphene growth. Currently several methods such as mechanical exfoliation, epitaxial growth on SiC substrates and chemical vapor deposition (CVD) have been developed. By mechanical exfoliation method, small and random high-quality graphene flakes are always obtained, which is not suitable for large-scale production.<sup>[14]</sup> The sublimation of SiC in vacuum can obtain a high-quality of graphene. However, it suffers from the high product cost and transfer problems.<sup>[15]</sup> In all these methods, CVD has been proved to be an inexpensive way of obtaining large scale graphenes. Reasonably high-quality graphene has been grown by using thermal CVD on different transition metals such as  $Ru_{,[16,17]}^{[16,17]} Pt_{,[18]}^{[18]} Ni_{,[19,20]}^{[19,20]}$ Pd,<sup>[21]</sup> Ir<sup>[22]</sup> or Cu.<sup>[23]</sup> In particular, the CVD growth on Cu foils has recently attracted increasing attention due to the fact that over a large area a uniform highquality single layer has been developed.<sup>[24-27]</sup> Growth of high quality bilayer graphene is more challenging. Recently bilayer graphene has also been synthesized on Cu foil by using thermal CVD at slow cooling rate or carefully controlling the Cu substrate.<sup>[28,29]</sup> However, normally very high-purity and quality Cu foil was required to synthesize large scale high-quality graphene, which results in relatively expensive production cost. To extend the industrial application of graphene, it is very important to further reduce the cost and to achieve reliable graphene products. Using cheap industrial Cu foils as substrates may dramatically lower the cost of growth graphene, and may promote the application of graphene.

In this Letter, we synthesize graphene on very cheap 25  $\mu$ m thick industrial Cu foils by low pressure chemical vapor deposition (LPCVD). Large scale homogenous graphenes have been synthesized by optimizing various growth parameters. Then the graphenes have been transferred onto SiO<sub>2</sub>/Si substrates. Raman spectra have been used to characterize the number of layers of graphene. Single-layer and bilayer graphenes can be obtained through carefully controlling the growth condition. Two terminals of bilayer graphene field effect transistors were fabricated by using standard electron-beam lithography. The mobility of the bilayer LPCVD graphene transistors reached 4000 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup> at room temperature.

The graphene was grown by thermal tube LPCVD process using common industrial Cu film as substrates. After carefully pre-treating the Cu foil, the Cu films were loaded into the quartz tube, and then

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vacuumed by rotary pump; a constant flow of  $H_2$  (30 sccm) was kept during the temperature ramping. The pressure is controlled by the quantity and type of gas. Carefully pre-treating the substrate, tuning the growth temperature, hydrocarbon concentrations and the growth time, the growth parameters have been optimized to synthesize homogenous layer controllable graphene.



Fig. 1. The typical low pressure chemical vapor deposition growth graphene procedure.

The typical growth parameters and process are shown in Fig. 1. Large size homogenous layer controllable graphene can be synthesized at different growth times with fixed growth temperature 935°C and hydrocarbon concentration 30 Pa. After the LPCVD synthesis of graphene, the graphene transferred onto Si/SiO<sub>2</sub> substrate process has been optimized. Raman spectra has been used to characterize the graphene properties. The bilayer graphene field effect transistors were fabricated by standard electron beam lithography and defined device structure by using O-plasma. The Ti/Au (5/45 nm) contacts were deposited by thermal evaporation. The patterned device was annealed at 400°C in  $H_2/Ar$  mixture gas for two hours before measurements. Then the field effect properties of the devices have been investigated by using Agilent B1500.

Common industrial Cu films  $(25 \,\mu\text{m} \text{ thick})$  were used as substrates in our experiments. The Cu films were first cleaned in acetone followed by ethanol. Then they were kept in acetic acid for 10 min to remove the impurities on the Cu surfaces. The Cu foil was then dried by nitrogen gas immediately before putting into the quartz tube. Keeping the surface of Cu foil away from water or moist condition has greatly improved the reproducibility of graphene growth due to the fact that the existence of water disturbs the deposition of graphene.

Some metals such as Ni, Fe and Co have been widely used to grow carbon nanotubes for their high catalytic efficiency.<sup>[30,31]</sup> However, they are not suitable for mono- or bilayer graphenes' growth due to their excellent capability to decompose hydrocarbons. On the contrary, the solubility of carbon in Cu is very low (<0.001 at.%), it is generally believed that monolayer graphene can be easily formed by diffusion of the carbon atom on the Cu substrate. Although the growth window for the synthesis of graphene seems very wide, our detailed experiments show that highquality graphene can only be obtained under certain conditions. In this study, we carefully optimized the growth parameters including the growth temperature, hydrocarbon concentration and growth time to obtain large scale homogenous graphene.

Growth temperature and the hydrocarbon concentration are very important parameters for obtaining high-quality graphene. To search for the best growth temperature, we performed the experiments under different growth temperatures varying from 900°C to 1000°C at constant gas flow of  $H_2(2)/CH_4$  (36 sccm) (50 Pa). It is found that relatively higher temperature was favored in the formation of larger grains, which effectively reduced the number of grain boundaries. However, there was an upper limit for the growth temperature. The Cu foil was partially melted and left a non-smooth surface when the temperature was higher than 935°C.



**Fig. 2.** The influence of temperature and hydrocarbon concentration on the growth of graphene: (a)  $T_{\rm g} = 950^{\circ}{\rm C}$  and hydrocarbon concentration 50 Pa; (b) $T_{\rm g} = 935^{\circ}{\rm C}$  and hydrocarbon concentration 50 Pa; (c)  $T_{\rm g} = 900^{\circ}{\rm C}$  and hydrocarbon concentration 50 Pa; (d)  $T_{\rm g} = 935^{\circ}{\rm C}$  and hydrocarbon concentration 200 Pa; (e)  $T_{\rm g} = 935^{\circ}{\rm C}$  and hydrocarbon concentration 100 Pa; and (f)  $T_{\rm g} = 935^{\circ}{\rm C}$  and hydrocarbon concentration 30 Pa.

When the growth temperature was higher than 960°C, the Cu foil was totally melted and small Cu balls were observed in the ceramic boat after the growth process. This temperature is lower than the melting point of pure Cu (1080°C) and could be originated from the relatively higher concentration of impurities in our industrial Cu foils. As shown in Figs. 2(a)-2(c), the optimal graphene synthesis temperature was determined to be 935°C in our LPCVD set up, where even-sized large crystalline grains have been formed. In the process of graphene growth, concentration of hydrocarbon is another important parameter. Usually, the Cu foils lost their metallic luster after CVD process when the concentration of CH<sub>4</sub> was not appropriate. To optimize the hydrocarbon concentration during the growth stage, the flow of  $CH_4$  was varied from 18 to 126 sccm with fixed growth time of 30 min at the optimized growth temperature  $T_{\rm g} = 935$  °C, where we fixed the relative ratio of  $CH_4$  and  $H_2$  (18:1). Correspondingly, the gas pressure in the growth chamber was changed from 30 to 210 Pa. Thus the gas pressure is then directly related to the concentration of  $CH_4$ . Thus we standardize the hydrocarbon concentration by gas pressure in this study. As shown in the optical images of Figs. 2(d)-2(f), the hydrocarbon concentration strongly affects the graphene growth. Relatively lower concentration of hydrocarbon is favorable for growth of even and large size graphene. Higher concentration of hydrocarbon made the even growth of graphene very difficult, usually thick graphite is formed on Cu substrates in this situation. Scanning electron microscopy (SEM) was also used to characterize the micro structure of graphene. The SEM images support our previous opinion, higher concentration of CH<sub>4</sub>, higher pressure and longer growth time leads to the formation of thick inhomogeneous graphene as shown in Figs. 3(a)and 3(b), where the white spots are the multilayer graphene or graphite. As shown in Figs. 3(c) and 3(d), very homogenous graphene was synthesized on the Cu surface at low  $CH_4$  concentration (30 Pa).



**Fig. 3.** The scanning microscopy images of graphene grown at different hydrocarbon concentrations and different growth time with fixed growth temperature  $T_{\rm g} = 935$ °C: (a) hydrocarbon concentration 100 Pa and growth time 10 min; (b) hydrocarbon concentration 50 Pa and growth time 10 min; (c) hydrocarbon concentration 30 Pa and growth time 10 min; and (d) hydrocarbon concentration 30 Pa and growth time 5 min.

Growth time is another very important parameter in determining the formation of graphene on Cu substrates as shown in Figs. 4(a)-4(f). The color of the Cu foil was turned into dark red after 30 min LPCVD growth at temperature 935°C when the concentration of hydrocarbon is high (50 Pa or above) as shown in Figs. 2(d), 2(e) and 4(a). It suggests that the Cu foil was not covered with graphene and has been oxidized. However, as shown in Fig. 4(b), only part of the Cu foil surface slowly turned dark after shrinking the graphene synthesis time to 20 min at 100 Pa.



Fig. 4. The influence of growth time and the hydrocarbon concentration on the growth of graphene at fixed growth temperature  $T_{\rm g} = 935$ °C: (a) hydrocarbon concentration 100 Pa and growth time 30 min; (b) hydrocarbon concentration 100 Pa and growth time 20 min; (c) hydrocarbon concentration 50 Pa and growth time 10 min; (d) hydrocarbon concentration 30 Pa and growth time 30 min; (e) hydrocarbon concentration 30 Pa and growth time 10 min; (f) hydrocarbon concentration 30 Pa and growth time 2 min. Insets of (d)–(f): the corresponding high resolution of optical images of (d)–(f).



Fig. 5. The optical images of transferred graphene onto  $Si/SiO_2$  substrates: (a) without HCl treatment, (b) with 5 h 5% HCl treatment.

Reducing the growth time further, the Cu foil surface was kept rather bright with 10 min growth time at 50 Pa. Our results proved that the growth time is really an important parameter to obtain high-quality graphene of LPCVD growth on Cu substrates. We then focused on the optimization of the growth time at fixed low hydrocarbon concentration (30 Pa) and growth temperature 935°C. Varying the growth time from 2 to 30 min, the Cu foils after growth are all very bright and they show very similar macro-scale view. However, as shown in the insets of Figs. 4(d)-4(f), small size dark spots can be observed in high resolution optical images, indicating the discontinuous growth of graphene. Comparing these three figures, the density of defects is the highest in  $2 \min$  grown sample and is the lowest in the 10 min grown sample. It convinces us that we can control the defect density through carefully controlling the growth time.

After the graphenes have been synthesized by using the optimized LPCVD growth process, a thin layer of polymethyl methacrylate (PMMA) was spin-coated on one side of the shiny sample. Then the sample was kept in the mixture of iron chloride (Sigma Aldrich) solution (1N) and diluted hydrochloric acid for at least 12 h. After the Cu substrate was totally removed, deionized water was used to dilute and wash for several times to remove the residues. Then the graphene was transferred onto  $Si/SiO_2$  substrates. However, still many very small particles were observed using optical microscopy as shown in Fig. 5(a), indicating the presence of some undissolved particles either from the non-high purity Cu foil or during the etching process.

To further improve the transfer process, the sample was kept in the diluted HCl solution (5%) for at least 5 h before being washed using deionized water. Then the aggregated impurities of the transferred graphene onto Si/SiO<sub>2</sub> substrates were dramatically reduced as shown in Fig. 5(b). The transferred graphene prepared by this method is very clean and homogenous, indicating the importance of the use of HCl solution for transferring graphene.



Fig. 6. The Raman spectrum of graphene at different growth times (5 min, 10 min, 20 min and 30 min) with fixing the optimized growth temperature 935°C and hydrocarbon concentration 30 Pa. The intensity of  $I_D/I_G$  and  $I_{2D}/I_G$  ratios are also shown.

At the fixed optimized growth temperature 935°C and hydrocarbon concentration at 30 Pa, the graphenes produced at different growth time were transferred to Si/SiO<sub>2</sub> substrates. We used Raman spectroscopy at wavelength 532 nm to investigate the physical properties of the graphenes. Raman spectroscopy is a very powerful method to characterize the CVD grown graphene. As shown in Fig. 6, there are three distinguished bands that can be found in Raman spectra for the measured graphenes for different growth times. Similar Raman spectra were obtained in more than 10 randomly picked up spots across a few millimeters of the different films, indicating the very homogenous nature of the LPCVD growth graphene at these growth conditions. The two most pronounced bands are the G band (around  $1580 \,\mathrm{cm}^{-1}$ ) and the 2D band (around  $2650 \,\mathrm{cm}^{-1}$ ), where the G band originates from in-plane vibration of  $sp^2$  carbon atoms<sup>[32]</sup> and the 2D band originates from the double-resonance processes of the two phonons with opposite momentum in the highest optical branch near the K points in the Brillouin zone.<sup>[33]</sup> G and 2D peak positions are related to the doping level of graphene. The full width at half maximum (FWHM) of the 2D band is a very important signature for the layers of the graphene. The cut-off full width at half-maximum (FWHM) of the 2D peak for single layer of graphene is  $30 \text{ cm}^{-1}$ . The 2D band FWHM that was observed monotonically increases with the increasing number of graphene layers from monolayer to fiver layers.



Fig. 7. (a) The optical images of the fabricated bilayer graphene field effect transistors. (b) The typical sheet resistance versus back gate voltages at fixed source drain voltage at 1 mV.

The 2D FWHM of exfoliate bilayer graphene and CVD growth bilayer graphene was found to be 46 and  $43-53 \,\mathrm{cm}^{-1}$ , respectively. For the trilayer exfoliate and CVD growth graphene, the 2D FWHM was found to be 56 and  $63 \,\mathrm{cm}^{-1}$ , respectively.<sup>[28]</sup> The FWHM of 2D band is  $27 \,\mathrm{cm}^{-1}$  for our 5 min growth graphene. However, surprisingly the 2D band FWHM is almost constant of  $\sim 44 \,\mathrm{cm}^{-1}$  for the graphenes with growth time from 10 to 30 min. The ratio of  $I_{2D}/I_{G}$ is also dependent on the number of the graphene layers.<sup>[34,35]</sup> The Raman spectra of LPCVD-grown graphene (transferred from Cu) showed an  $I_{2D}/I_{\rm G} \sim 2$ to indicate monolayer graphene, 1  $< I_{\rm 2D}/I_{\rm G} < 2$ for bilayer graphene.<sup>[23]</sup> As shown in Fig. 6, the 2Dto-G intensity ratio monotonically decreases from 1.9 at 5 min growth time down to 0.6 at 30 min growth time. From the intensity of  $I_{\rm 2D}/I_{\rm G}$  and the 2D band FWHM, we can conclude that the monolayer graphene can be synthesized at short growth time  $\sim 5 \,\mathrm{min.}^{[36]}$ The 2D FWHM still keeps constant of  $44 \,\mathrm{cm}^{-1}$  with the increasing growth time although the magnitude of  $I_{\rm 2D}/I_{\rm G}$  decreases. The intensity ratio of  $I_{\rm 2D}/I_{\rm G}$  can decrease with the increasing doping level at fixed layers of CVD growth graphene.<sup>[37]</sup> It suggests that the bilayer graphene was obtained during a wide growth time window from 10 to 30 min. A much smaller D band was observed in the Raman spectra at around  $1320 \,\mathrm{cm}^{-1}$ , which is related to the defects in graphene. The measured D band and G band intensity ratio of  $I_{\rm D}/I_{\rm G}$  directly reflects the defects density of graphene. As shown in Fig. 6, very low value of  $I_{\rm D}/I_{\rm G}$  was found in the 10 and 20 min growth graphene, while the magnitude of  $I_{\rm D}/I_{\rm G}$  was relatively larger for the 5 and 30 min growth graphene, which can be supported with the existance of weak D' band of these two curves.<sup>[38]</sup> Our results show that the growth time is not only important to the number of layers, but also important

to the quality of graphene. Compared to the growth time dependence of the graphene Raman spectra, the growth of graphene on the Cu surface was found to be a self-ceasing process at about bilayer graphene with the low solubility of carbon in Cu. The low pressure and impurities may reduce the solubility of carbon in Cu at this growth temperature. Both the homogenous single layer and bilayer graphenes can be synthesized under our optimized growth condition.

We are very interested in the graphene electronics. Since bilayer graphene has an electric field controllable bandgap and is very promising for future electronics, the two terminal bilayer graphene onto  $Si/SiO_2$  field effect transistor devices have been fabricated, which is shown in Fig. 7(a). Current intensity linearly increases with increasing the source drain voltage for all measured devices, indicating the ohmic contact between the graphene and the bondpads.

At fixed source-drain voltage  $V_{\rm SD} = 1 \,\mathrm{mV}$ , all our LPCVD growth bilayer graphene devices show bipolar behavior with scanning the back gate voltages. However, the neutral (Dirac) points of all the measured devices shift to positive gate voltage. The neutral point of the device shown in Fig. 7(b) shifts to 22 V, indicating unintentional p-type doping CVD growth graphene of  $1.2 \times 10^{12} \,\mathrm{cm}^{-2}$ . The carrier mobility  $\mu$  can be calculated from  $\mu = (L/WC_g R^2) dR/dV_g$ , where  $L = 14 \,\mu\text{m}$  is the channel length,  $W = 5 \,\mu\text{m}$ is the channel width,  $V_{\rm g}$  is back gate voltage and  $C_{\rm g}~=~115\,{
m aF}/{
m \mu m^2}$  is the capacitance between the channel and the back gate per unit area ( $C_{\rm g} = \varepsilon \varepsilon_0 / d;$  $\varepsilon = 3.9; d = 300 \,\mathrm{nm}$ ). The carrier mobility of the bilayer graphene is calculated to be  $4300 \,\mathrm{cm}^2 \mathrm{V}^{-1} \mathrm{s}^{-1}$ . which is good enough for most of the electronic applications.

In summary, using low pressure chemical vapor deposition, we have carefully tuned the growth parameters including growth temperature, growth time and the hydrocarbon concentration for growing graphene on very cheap industrial Cu foils. We find that the high-quality graphene can only be synthesized under certain conditions. The best growth temperature in our facility is 935°C, and the hydrocarbon concentration is 30 Pa. Large-sized homogenous single-layer and bilayer graphenes can be synthesized at different growth times with fixed optimized growth temperature and hydrocarbon concentration. Raman analysis indicates that the number of the graphene layers can be controlled by the growth time. We find that the growth of graphene on Cu surfaces is self ceasing at bilayer graphene with the low solubility of carbon in Cu. Furthermore, CVD grown graphene was transferred onto SiO<sub>2</sub>/Si substrates, and the mobility of the bilayer graphene field effect transistors is about  $4300 \,\mathrm{cm}^2 \mathrm{V}^{-1} \mathrm{s}^{-1}$  at room temperature. Our experiments show that the common Cu foil can be used to grow homogenous single and bilayer graphene, which could be widely used in future industrial graphene applications.

## References

- [1] Novoselov K S et al 2004 Science 306 666
- [2] Zhang Y B et al 2005 Nature **438** 201
- [3] Stoller M D et al 2008 Nano Lett. 8 3498
- [4] Liu M et al 2011 Nature **474** 64
- [5] Xia F N et al 2009 Nat. Nanotechnol. 4 839
- [6] Pan H L et al 2011 Chin. Phys. Lett. 28 127202
- [7] Han M Y et al 2007 Phys. Rev. Lett. 98 206805
- [8] Liu H et al 2010 Chin. Phys. Lett. 27 077201
- [9] Li X L et al 2008 Science **319** 1229
- [10] Zhou S Y et al 2007 Nat. Mater. 6 770
- [11] Giovannetti G et al 2007 Phys. Rev. B 76 073103
- [12] Zhang Y B et al 2009 Nature **459** 820
- [13] Yu W J and Duan X F 2013 Sci. Rep. 3 1248
- [14] Novoselov K S et al 2005 Nature **438** 197
- [15] Emtsev K V et al 2009 Nat. Mater. 8 203
- [16] Sutter P W, Flege J I and Sutter E A 2008 Nat. Mater. 7 406
- [17] Pan Y et al 2009 Adv. Mater. 21 2777
- [18] Gao L B et al 2012 Nat. Commun. 3 699
- [19] Reina A et al 2009 Nano Lett. 9 30
- [20] Iwasaki T et al 2011 Nano Lett. **11** 79
- [21] Kwon S Y et al 2009 Nano Lett. 9 3985
- [22] Coraux J et al 2008 Nano Lett. 8 565
- [23] Li X S et al 2009 Science **324** 1312
- [24] Lee Y et al 2010 Nano Lett. 10 490
- [25] Liu W et al 2011 Carbon 49 4122
- [26] Petrone N et al 2012 Nano Lett. **12** 2751
- [27] Bae S et al 2010 Nat. Nanotechnol. 5 574
- [28] Lee S, Lee K and Zhong Z H 2010 Nano Lett. 10 4702
- [29] Nie S et al 2012 New J. Phys. 14 093028
- [30] Hofmann S et al 2007 Nano Lett. 7 602
- [31] Kukovecz Á et al 2000 Phys. Chem. Chem. Phys. 2 3071
- [32] Pimenta M A et al 2007 Phys. Chem. Chem. Phys. 9 1276
- 33] Thomsen C and Reich S 2000 Phys. Rev. Lett. 85 5214
- [34] Hao Y F et al 2010 Small 6 195
- [35] Ferrari A C et al 2006 Phys. Rev. Lett. 97 187401
- [36] Malard L M et al 2009 Phys. Rep. 473 51
- 37] Tongay S et al 2011 Nanotechnology 22 425701
- [38] Iqbal M W et al 2012 J. Phys.: Condens. Matter 24 335301