

Available at www.sciencedirect.com

# **SciVerse ScienceDirect**



journal homepage: www.elsevier.com/locate/carbon

# High-quality and efficient transfer of large-area graphene films onto different substrates

Xu-Dong Chen<sup>a</sup>, Zhi-Bo Liu<sup>a,\*</sup>, Chao-Yi Zheng<sup>a</sup>, Fei Xing<sup>a</sup>, Xiao-Qing Yan<sup>a,b</sup>, Yongsheng Chen<sup>b</sup>, Jian-Guo Tian<sup>a</sup>

<sup>a</sup> The Key Laboratory of Weak Light Nonlinear Photonics, Ministry of Education, Teda Applied Physics School and School of Physics, Nankai University, Tianjin 300071, China

<sup>b</sup> The Key Laboratory of Functional Polymer Materials and Center for Nanoscale Science & Technology, Institute of Polymer Chemistry, College of Chemistry, Nankai University, Tianjin 300071, China

#### ARTICLE INFO

Article history: Received 16 October 2012 Accepted 8 January 2013 Available online 25 January 2013

## ABSTRACT

We used a two-layer structure consisting of polyethylene terephthalate (PET) and silicone to transfer graphene grown by chemical vapor deposition onto various rigid and flexible substrates through dispersive adhesion. It only takes a few seconds to transfer graphene from PET/silicone to the target substrates at ambient conditions. And the recycling of the PET/silicone decreases the production cost greatly. The transferred graphene films were characterized by optical and atomic force microscopy, Raman spectroscopy, electrical analyses, and optical transmittance measurements, and the results show that the graphenes transferred by PET/silicone have a cleaner and more continuous surface, lower doping level, and higher optical transmittance and conductivity than those transferred by thermal release tape. Considering its high efficiency, low cost, large area and high quality, the PET/silicone transfer method would be particularly useful for graphene's electronic applications such as field-effect transistors and transparent conducting electrodes.

© 2013 Elsevier Ltd. All rights reserved.

# 1. Introduction

Since the first graphene was obtained by mechanical exfoliation of highly ordered pyrolytic graphite in 2004 [1], it has been intensively studied due to its extraordinary mechanical, thermal and electrical properties, such as high carrier mobility, superelastic mechanical behavior, and ultraelectrical conductivity with high optical transmittance [2–5]. In despite of the high quality of the mechanical exfoliation graphene, it is hard to meet the need for mass fabrication of large-area uniform graphene. Large-area graphene is typically produced *via* epitaxial growth on SiC substrates [6], and chemical vapor deposition (CVD) on metal surface [7]. Considering its low cost and high efficiency, high quality, and large area, CVD-grown graphene is promising for industrial applications. To fabricate

\* Corresponding author: Fax: +86 22 23499981.

E-mail address: rainingstar@nankai.edu.cn (Z.-B. Liu).

devices such as field-effect transistors (FET) and transparent conducting electrodes, it is necessary to transfer graphene onto different substrates with high efficiency, low cost, large area and high quality.

Various methods have been developed to transfer graphene onto different substrates [3–5,8–17]. Currently, the most commonly used transfer methods rely on polymethylmethacrylate (PMMA) [4,8–11] or thermal release tape (TRT) [3,12,16] to support the graphene film and to prevent folding while the growth substrate is etched. However, both of those two materials have their own disadvantages. For instance, PMMA is not suitable for the transfer of large-area graphene films, because it is easy to introduce contamination, cracks and tears during the transfer process [8,10], and requires high handling skills. For TRT, while it can be easily used to transfer

<sup>0008-6223/\$ -</sup> see front matter © 2013 Elsevier Ltd. All rights reserved. http://dx.doi.org/10.1016/j.carbon.2013.01.011

large-area graphene onto rigid and flexible substrates than PMMA [3,16], it invariably contaminates the transferred graphene surface with adhesive from TRT [10,16]. The residual adhesive affects seriously the performance of graphene in optical and electrical applications. It is necessary to develop a new efficient method for the transfer of graphene with the scale and quality required in the research and industrial applications.

The adhesion of polymer supports (i.e., PMMA and TRT) to the graphene mainly depends on the viscosity of the polymer film. The residual PMMA or adhesive left on the graphene surface is inevitable. To get a clean surface, we select dispersive adhesion, also known as physisorption, to replace the adhesives. The transfer mechanism with dispersive adhesion is discussed in Supplementary Information (SI). Due to the reversible process of the dispersive adhesion without using any chemical adhesives, the graphene surface will keep clean after desorption process. In this paper, we used a two-layer structure of polyethylene terephthalate (PET) and silicone, PET layer for support and silicone layer for dispersive adhesion, to transfer graphene onto arbitrary substrates with high efficiency, high quality and large scale. The Attenuated Total Reflection Flourier Transformed Infrared (ATR-FTIR) spectrum of the silicone (see Fig. S1, SI) shows that the silicone contains Si–O–Si and Si–(CH<sub>3</sub>)<sub>2</sub> groups [18]. Due to the low surface tension of the silicone, graphene can be released on arbitrary substrates successfully. And owing to the reversible process of the dispersive adhesion, the recyclable use of the PET/silicone can be achieved to reduce the production cost. Now the technology for the production of the materials with two-layer structure has been very mature, such as the screen protector for iPad and iPhone, making it possible for large-area graphene transfer in industrial applications.

For comparison, we transferred graphene films to rigid and flexible substrates (i.e., SiO<sub>2</sub>/Si wafer and PET) by TRT and PET/ silicone, respectively. The transferred graphene films were characterized with optical microscopy, atomic force microscopy (AFM), Raman spectrum, electrical analyses and optical transmittance measurement. Compared with the TRT method, the graphene transferred by PET/silicone had a cleaner and more continuous surface, lower doping level, and higher optical transmittance and conductivity. Four graphene films were transferred by a recycled PET/silicone successfully, with clean and continuous surfaces. We also transferred graphene onto different rigid and flexible substrates with PET/silicone successfully.

# 2. Experimental

#### 2.1. Preparation and transfer of graphene

The commercial screen protector used to transfer graphene in this work was Capdase iMAG Screen Protector for iPhone 4/4S. The thicknesses of the PET and silicone layers were about 100 and 60  $\mu$ m, respectively. The single-layer and multi-layer graphene on copper foil we used in the experiments were ACS Material Graphene/Cu. The TRT and high n-doped SiO<sub>2</sub>/Si wafers with 285 nm oxide were bought from the Graphene Supermarket. A two-component polydimethylsiloxane

(PDMS) from Dow Corning (SYLGARD<sup>®</sup> 184) was cured at 75 °C for 1 h with a 10:1 base to curing agent mixing ratio. The FeCl<sub>3</sub> (Analytical reagent,  $\geq$ 99%), hydrochloric acid (Analytical regent, 37%), and Chloroform (Analytical reagent,  $\geq$ 99%) were produced by Jiangtian reagent company. PMMA (average  $M_w \sim$ 996,000 by GPC, crystalline, Aldrich) were bought from the Sigma–Aldrich.

The graphene/Cu sample was first flattened between two cleaned glass slides and then attached to the PET/silicone film with dispersive adhesion. In order to make the PET/silicone fully adhere onto the rough substrate with micro-rolling, a pressure of 0.05 MPa was applied on it for 1 h. The underlying Cu foil was etched in FeCl<sub>3</sub> solution (1 M) for 1 h. After rinsed with deionized water to remove residual etchant, the PET/silicone/graphene stack was rinsed in 10% HCl (60 °C) for half an hour to remove residual  $Fe^{3+}$  ions. The sample was rinsed with deionized water to remove residual HCl solution and then dried with N<sub>2</sub>. The PET/silicone/graphene stack was attached to the new substrates such as SiO<sub>2</sub>/Si wafer and PET film with dispersive adhesion. Lastly, the PET/silicone film was peeled off and the graphene was transferred to the new substrate successfully. The surfaces of the target materials are pristine without any treatment.

#### 2.2. FET fabrication

After the 3-layer graphene films transferred to the SiO<sub>2</sub>/Si wafer, metal electrodes were deposited on the surface by metal mask. And then the FETs were annealed at 120 °C for 1 h under vacuum to remove water and air doping on the graphene.

#### 2.3. Characterization

The ATR-FTIR spectrum was recorded on a Nexus 870 FTIR spectrometer. The surface morphology of transferred graphene on SiO<sub>2</sub>/Si wafer was investigated by optical microscopy (Nikon ECLIPSE Ti-U) and AFM (MultiMode™). Raman spectra were carried out using RENISHAW RM2000 Raman System equipped with a 514 nm laser source and  $50 \times objective$  lens. To obtain the Raman images, samples were moved with a step size of 1 µm and a Raman spectrum was recorded at every point. The region we measured was  $20 \times 20 \,\mu$ m. The transfer characteristic curves were measured by using an Agilent 34401A Digit Multimeter. The optical transmittance spectroscopy measurement was performed using HITACHI U-4100 Spectrophotometer. The sheet resistance of the graphene was measured using Accent HL5550 Hall Effect Measurement System. The contact angles were measured with a video contact angle system (JC2000C).

# 3. Results and discussion

Fig. 1 gives the schematic diagram of the dry transfer of CVD-grown graphene onto arbitrary substrates, such as  $SiO_2/Si$  wafer and PET film. There are three essential steps in the PET/silicone transfer process: 1. adhesion of the PET/silicone to the graphene/Cu; 2. etching of the Cu layer; 3. release of the graphene layer and transfer onto the target substrate. The main difference between PET/silicone and the



Fig. 1 – Schematic illustration of (a) graphene transfer by PET/silicone and (b) the designed two-layer structure. (c and d) Photographs of large-area graphene film transferred by PET/silicone onto SiO<sub>2</sub>/Si wafer and PET film, respectively.

other two methods is the third step. PMMA is removed by solvent rinsing [4,8–11], and TRT is released at 125 °C under a certain pressure [3,12,16]. For the PET/silicone, it can be peeled off directly at ambient conditions after the PET/silicone/ graphene is attached to the target substrate, leaving graphene on the substrate. Fig. 1c and d show the transferred 6-layer graphene films on SiO<sub>2</sub>/Si wafer and PET film with the size larger than 1 inch, respectively. Limited by the size of the graphene/Cu samples we bought, graphene films with larger scale were not transferred. But we all believe that the scale of the graphene transferred by PET/silicone can be as large as that transferred by TRT [3,12,16]. This is because the structures of the PET/silicone and TRT are similar: a thin polymer film coated with an adhesive layer. This structure is important to the large-area graphene transfer [3,5,12,16], because the support layer makes the transfer process much easier than PMMA. What's more, the production technology of the PET/ silicone has been very mature today, making it possible for large-area graphene transfer in industrial applications.

The graphene transfer from silicone to an acceptor substrate is mainly governed by the difference of work of adhesion involved in the surface tension of each layer. In order to transfer graphene, the work of adhesion at the graphene and the target substrate interface should be higher than that at the silicone and graphene interface [19,20]. The surface tension of the silicone used in the current work was 15.6 dyn cm<sup>-1</sup>, which was calculated from the geometricmean method. The calculation of the surface tension and work of adhesion are shown in SI. The surface tension of the silicone is quite small compared with other substrates (Table S1, SI), and oxygen plasma treatment can enhance the surface tension of the target substrates greatly [19]. As a result, graphene can be transferred onto almost arbitrary substrates by PET/silicone.

In order to improve the transfer efficiency, the release time should be as short as possible. Fig. S2 in SI shows the optical images of 3-layer graphene transferred onto  $SiO_2/Si$ wafers by PET/silicone with different release time. The wrinkles of the graphene films were not introduced during the transfer process, but came from the graphene/Cu samples we bought (see Fig. S3, SI). Due to the rapid desorption process of the dispersive adhesion, it takes a few seconds to release graphene from PET/silicone to the target substrates at ambient conditions without additional pressure, which is much less than PMMA and TRT. Thus, we can conclude that it is a simple and rapid way to transfer large-scale graphene by PET/silicone onto various substrates, only limited by the size of graphene. Actually, PDMS assisted transfer is another typical method and the transfer process used in this work is similar to the PDMS method. However, PET/Silicone can release graphene to the target substrate in a very short time without any pressure, but PDMS can't do it (see the video in SI). Fig. S4 in SI shows the results of the 3-layer graphene transferred to PET film by PET/Silicone and PDMS with different pressure and release time. The results show that the pressure has little effect on transfer integrity for the PET/Silicone, but the transfer integrity of PDMS is sensitive to the pressure and release time. This is because the work of adhesion at the PET/Silicone and graphene interface is smaller than that at PDMS/graphene interface, making it much easier to transfer graphene to the target substrates compared to PDMS.

More attractively, due to the reverse process of the dispersive adhesion, silicone can be used again after the graphene is transferred to the substrates. As show in Fig. 2, a recycled PET/silicone was used to transfer four graphene films onto SiO<sub>2</sub>/Si wafers successfully. In our experiments, one PET/Silicone can transfer about 5–6 graphene films to target substrates in high quality. Then due to the gradual adsorption of contamination to the silicone during the transfer processes, the graphene at the edge of the graphene/Cu samples could be hardly attached to the silicone layer, leading to an incomplete transfer (see Fig. S5, SI). However, the PET/Silicone can be used more times if the experiment environment is cleaner. The recycling of the PET/silicone will decrease the production cost greatly.



Fig. 2 – Optical images of 3-layer graphene transferred onto  $SiO_2/Si$  wafer by one recycled PET/silicone. (a) the first, (b) the second, (c) the third, and (d) the fourth cycles. The insets show the photographs of the graphene samples. The objective lens is  $10\times$ .



Fig. 3 – (a–c) Optical and (d–f) 3D AFM images showing the surface morphologies of the monolayer graphene films transferred onto  $SiO_2/Si$  substrates by TRT, PMMA and PET/silicone, respectively. Many residues (arrows) and cracks (circles) can be seen. The insets show the photographs of the samples. The objective lens is  $20\times$ .

For an ideal transfer, the graphene surface should keep clean and continuous. The microscopy-image is a common way to present the surface morphology of graphene film. Fig. 3 shows the optical and AFM images of monolayer graphene films  $(1 \times 1 \text{ cm}^2)$  on SiO<sub>2</sub>/Si wafers transferred by TRT, PMMA, and PET/silicone, respectively. We can see that the



Fig. 4 – Raman mapping images and corresponding spectra of the pristine graphene/Cu and single-layer graphene films on SiO<sub>2</sub>/Si substrates transferred by PET/silicone, TRT and PMMA, respectively. (a–d) The Raman images of the single-layer graphene before and after transfer by extracting the intensity of 2D/G ratio. (e–h) The Raman spectra of four samples recorded at the points which are marked in (a–d).

TRT and PMMA transferred graphenes contain many residues, and some cracks and tears in the PMMA transferred sample (Fig. 3a and b), but the PET/silicone sample shows a clean and continuous morphology with very few defective structures (Fig. 3c). The residues left on the graphene surface transferred by TRT, also observed by other groups [10,16], are the adhesive from the TRT. These residual adhesive are difficult to clean and will negatively affect the performance

of graphene devices. For the case of PMMA transfer, residual PMMA and other residues from solvents used to remove the PMMA are the main contamination, which has been demonstrated in previous papers [10,17]. Although a "modified Radio Corporation of America clean" method has been developed to control the contamination and crack formation [10], this method is much more complex than other methods. It has been reported that graphene films tend to break at the last PMMA removal step [8,10]. When transferred from water to the target substrate, the PMMA/graphene does not make full contact with the substrate, and the unattached regions tend to break and form cracks. Different from the TRT and PMMA, there will be no residues on graphene after the PET/silicone transfer process, because the adhesion of the PET/silicone and graphene is achieved by the dispersive adhesion. And due to the support of the PET layer, PET/silicone/graphene stack can be attached to the substrate completely. As a result, we got a clean and continuous surface by the PET/silicone transfer method. The AFM images of the three samples in Fig. 3 also show that the PET/silicone transferred graphene has a much uniform morphology with less contamination than the graphene films transferred by TRT and PMMA.

The Raman spectra is a quick and unambiguous method to evaluate the quality and the number of graphene layers [7,21-23]. The difference of the D, G and 2D peak presents the quality and uniformity of the graphene. Fig. 4 shows the Raman images of single-layer graphene before and after transfer by extracting the intensity of 2D/G ratio, and Raman spectra of the corresponding points. It has been demonstrated that the increase of the 2D/G ratio indicates a cleaner surface with lower doping level [17,23]. The Raman mapping images show that the 2D/G ratio of the graphene transferred by PET/silicone is larger than that of the graphene transferred by TRT and PMMA, and quite similar to the pristine graphene/Cu sample, indicating a better quality and uniformity. Compared with the other two samples, the D peak of the PET/silicone transferred graphene is the lowest, suggesting that the graphene is well-transferred on the wafer without obvious damage. Here we suppose that the occurrence of the D peak is due to the residues or wrinkles formed during the transferred process [3,4,16].

After graphene has been successfully transferred onto  $SiO_2/Si$  wafer, it is ready to be fabricated into electronic devices. FET measurement of ideal graphene is expected to

have the linear dispersion "V" shape response of drain current  $I_{ds}$  versus back gate voltage  $V_g$  with the Dirac point at zero gate bias [17]. The shift of the Direct point exhibits the doping level of the graphene. Fig. 5 shows the transfer characteristic curves of the 3-layer graphene FETs on SiO<sub>2</sub>/ Si wafers transferred by TRT and PET/silicone, after annealing in high vacuum. The results show that the n-doping of the graphene transferred by TRT is much higher than the PET/silicone sample, indicating a stronger doping level introduced by the TRT transfer process. Graphene FETs exhibit ptype properties likely due to doping by  $O_2$  and  $H_2O$  [24–26], but the doping can be removed by gently heating in high vacuum [17,24]. Several reports have demonstrated that graphene samples with residual contamination show strong n-type doping [17,27]. When residual adhesive is left on graphene, charge transfer evidently occurs at the interface between graphene and the adhesive. The AFM image of the PET/Silicone transferred graphene shows that there is still some contamination on the graphene surface. So the ndoping is mainly introduced from the residual adhesive and contamination. The insets in the Fig. 5 are the photographs of the two PET samples. The shape of the graphene on the TRT transferred FET can be seen clearly, due to the thick residual adhesive layer on the graphene surface. Fig. S6 in SI shows the Raman spectra of the 3-layer graphene used to fabricate the FETs. The Raman spectra of the two samples are all have a high intensity of D band, which indicates the doping of graphene [28].

One of the promising applications of graphene is as a transparent conductive electrode owing to its high optical transmittance and conductivity [8-11]. Fig. S7a in SI shows the optical transmittance of the single-layer and 3-layer graphene on the PET films transferred by TRT and PET/silicone, respectively. As a result of the residual adhesive, the optical transmittance of the TRT transferred graphene is lower. The optical transmittance of the PET/Silicone transferred 3-layer graphene on PET is 85% at 550 nm (Fig. S7b, SI), which is higher than carbon nanotubes [29]. And then we measured the sheet resistance of the samples (see Fig. S7a, SI). The sheet resistance of the TRT transferred graphene is higher, due to the large number of residual adhesive left on the surfaces. The PET/silicone transferred graphene films have high optical transmittance and conductivity, making them suitable for transparent and flexible electrodes.



Fig. 5 – Typical transfer characteristic curves of graphene FETs. The FETs were fabricated from 3-layer graphene films on SiO<sub>2</sub>/Si substrates transferred by (a) PET/silicone and (b) TRT. The insets show the photographs of the FETs.

We also transferred graphene films with PET/silicone onto some other rigid and flexible substrates successfully, such as quartz, PDMS, glass and PET film (Fig. S8, SI), which would be of broad interest as substrates for transparent conductive film. The PET/silicone composite material can be particularly useful for electronic applications.

# 4. Summary

We used a PET/silicone that combined the two-layer structure and dispersive adhesion to transfer large-area graphene in high quality. The time-saving release of graphene improves efficiency of the transfer, and the recyclable use of the PET/silicone decreases the production cost greatly. Due to the low surface tension of the PET/silicone, graphene can be transferred onto arbitrary substrates with high quality, which were evidenced by optical, AFM images, Raman spectroscopy, electrical analyses, and optical transmittance measurement. Compared with the graphene transferred by TRT, the graphenes transferred by PET/silicone have a cleaner and more continuous surface, lower doping level, and higher optical transmittance and conductivity. The PET/silicone transfer method would be particularly useful for electronic applications such as FETs and transparent conducting electrodes due to its high efficiency, low cost, large area, and high quality.

# Acknowledgments

The authors thank The Chinese National Key Basic Research Special Fund (Grant 2011CB922003), The Natural Science Foundation of China (Grant 10974103, 11174159), The Program for New Century Excellent Talents in University (NCET-09-0484), and The China Postdoctoral Science Foundation funded project (Grant 2012M510743).

# Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/ j.carbon.2013.01.011.

#### REFERENCE

- Novoselov KS, Geim AK, Morozov SV, Jiang D, Zhang Y, Dubonos SV, et al. Electric field effect in atomically thin carbon films. Science 2004;306(5696):666–9.
- [2] Kim KS, Zhao Y, Jang H, Lee SY, Kim JM, Kim KS, et al. Largescale pattern growth of graphene films for stretchable transparent electrodes. Nature 2009;457(7230):706–10.
- [3] Bae S, Kim H, Lee Y, Xu X, Park J, Zheng Y, et al. Roll-to-roll production of 30-inch graphene films for transparent electrodes. Nat Nanotechnol 2010;5(8):574–8.
- [4] Reina A, Son H, Jiao L, Fan B, Dresselhaus MS, Liu ZF, et al. Transferring and identification of single- and few-layer graphene on arbitrary substrates. J Phys Chem C 2008;112(46):17741–4.
- [5] Unarunotai S, Koepke JC, Tsai C-L, Du F, Chialvo CE, Murata Y, et al. Layer-by-layer transfer of multiple, large area sheets of

graphene grown in multilayer stacks on a single SiC wafer. ACS Nano 2010;4(10):5591–8.

- [6] Berger C, Song Z, Li T, Li X, Ogbazghi AY, Feng R, et al. Ultrathin epitaxial graphite: 2D electron gas properties and a route toward graphene-based nanoelectronics. J Phys Chem B 2004;108(52):19912–6.
- [7] Li X, Cai W, An J, Kim S, Nah J, Yang D, et al. Large-area synthesis of high-quality and uniform graphene films on copper foils. Science 2009;324(5932):1312–4.
- [8] Li X, Zhu Y, Cai W, Borysiak M, Han B, Chen D, et al. Transfer of large-area graphene films for high-performance transparent conductive electrodes. Nano Lett. 2009;9(12):4359–63.
- [9] Jiao L, Fan B, Xian X, Wu Z, Liu ZF. Creation of nanostructures with poly(methyl methacrylate)-mediated nanotransfer printing. J Am Chem Soc 2008;130(38):12612–3.
- [10] Liang X, Sperling BA, Calizo I, Cheng G, Hacker CA, Zhang Q, et al. Toward clean and crackless transfer of graphene. ACS Nano 2011;5(11):9144–53.
- [11] Suk JW, Kitt A, Magnuson CW, Hao Y, Ahmed S, An J, et al. Transfer of CVD-grown monolayer graphene onto arbitrary substrates. ACS Nano 2011;5(9):6916–24.
- [12] Lee Y, Bae S, Jang H, Jang S, Zhu S, Sim S, et al. Wafer-scale synthesis and transfer of graphene films. Nano Lett 2010;10(2):490–3.
- [13] Verma VP, Das S, Lahiri I, Choi W. Large-area graphene on polymer film for flexible and transparent anode in field emission device. Appl Phys Lett 2010;96(20):203108.
- [14] Wang Y, Zheng Y, Xu X, Dubuisson E, Bao Q, Lu J, et al. Electrochemical delamination of CVD-grown graphene film: toward the recyclable use of copper catalyst. ACS Nano 2011;5(12):9927–33.
- [15] Bajpai R, Roy S, Jain L, Kulshrestha N, Hazra KS, Misra DS. Facile one-step transfer process of graphene. Nanotechnology 2011;22(22):225606.
- [16] Kang J, Hwang S, Kim JH, Kim MH, Ryu J, Seo SJ, et al. Efficient transfer of large-area graphene films onto rigid substrates by hot pressing. ACS Nano 2012;6(6):5360–5.
- [17] Ren Y, Zhu C, Cai W, Li H, Hao Y, Wu Y, et al. An improved method for transferring graphene grown by chemical vapor deposition. Nano 2012;7(1):1150001.
- [18] Bodas D, Khan-Malek C. Formation of more stable hydrophilic surfaces of PDMS by plasma and chemical treatments. Microelectron Eng 2006;83(4– 9):1277–9.
- [19] Kim H, Yoon B, Sung J, Choi D-G, Park C. Micropatterning of thin P3HT films via plasma enhanced polymer transfer printing. J Mater Chem 2008;18(29):3489–95.
- [20] Kang SJ, Kim B, Kim KS, Zhao Y, Chen Z, Lee GH, et al. Inking elastomeric stamps with micro-patterned single layer graphene to create high-performance OFETs. Adv Mater 2011;23(31):3531–5.
- [21] Dresselhaus MS, Jorio A, Hofmann M, Dresselhaus G, Saito R. Perspectives on carbon nanotubes and graphene Raman spectroscopy. Nano Lett 2010;10(3):751–8.
- [22] Ferrari AC, Meyer JC, Scardaci V, Casiraghi C, Lazzeri M, Mauri F, et al. Raman spectrum of graphene and graphene layers. Phys Rev Lett 2006;97(18):187401.
- [23] Casiraghi C, Pisana S, Novoselov KS, Geim AK, Ferrari AC. Raman fingerprint of charged impurities in graphene. Appl Phys Lett 2007;91(23):233108.
- [24] Schedin F, Geim AK, Morozov SV, Hill EW, Blake P, Katsnelson MI, et al. Detection of individual gas molecules adsorbed on graphene. Nat Mater 2007;6(9):652–5.
- [25] Leenaert O, Partoens B, Peeters FM. Adsorption of H2O, NH3, CO, NO2, and NO on graphene: a first-principles study. Phys Rev B 2008;77(12):125416.

- [26] Wehling TO, Lichtenstein AI, Katsnelson M. First-principles studies of water adsorption on graphene: the role of the substrate. Appl Phys Lett 2008;93(20):202110.
- [27] Geringer V, Subramaniam D, Michel AK, Szafranek B, Schall D, Georgi A, et al. Electrical transport and low-temperature scanning tunneling microscopy of microsoldered graphene. Appl Phys Lett 2010;96(8):082114.
- [28] Wei D, Liu Y, Wang Y, Zhang H, Huang L, Yu G. Synthesis of ndoped graphene by chemical vapor deposition and its electrical properties. Nano Lett 2009;9(5):1752–8.
- [29] Wu Z, Chen Z, Du X, Logan JM, Sippel J, Nikolou M, et al. Transparent, conductive carbon nanotube film. Science 2004;305(5688):1273–6.