RAPID COMMUNICATION

Effect of 6H-SiC (11$\bar{2}$0) substrate on epitaxial graphene revealed by Raman scattering*

Lin Jing-Jing(林菁菁), Guo Li-Wei(郭丽伟)†, Jia Yu-Ping(贾玉萍), Chen Lian-Lian(陈莲莲), Lu Wei(芦 伟), Huang Jiao(黄 郊), and Chen Xiao-Long(陈小龙)

Research & Development Center for Functional Crystals, Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, *China*

(Received 5 July 2012; revised manuscript received 6 September 2012)

A nonpolar SiC(11$\bar{2}$0) substrate has been used to fabricate epitaxial graphene (EG). Two EGs with layer numbers of 8–10 (referred to as MLG) and 2–3 (referred to as FLG) were used as representative to study the substrate effect on EG through temperature-dependent Raman scattering. It is found that Raman lineshifts of G and 2D peaks of the MLG with temperature are consistent with that of free graphene, as predicted by theory calculation, indicating that the substrate influence on the MLG is undetectable. While Raman G peak lineshifts of the FLG to that of the free graphene are obvious, however, its lineshift rate (-0.016 cm^{-1}/K) is almost one third of that (-0.043 cm^{-1}/K) of an EG on 6H-SiC (0001) in the temperature range from 300 K to 400 K, indicating a weak substrate effect from SiC (11$\bar{2}$0) on the FLG. This renders the FLG with a high mobility around 1812 cm$^2\cdot$V$^{-1}\cdot$s^{-1} at room temperature even with a very high carrier concentration about 2.95×10^{13} cm^{-2} (p-type). These suggest SiC (11$\bar{2}$0) is more suitable for fabricating EG with high performance.

Keywords: epitaxial graphene, 6H-SiC (11$\bar{2}$0), temperature dependent Raman scattering

PACS: 63.22.Rc, 63.20.Ry **DOI:** 10.1088/1674-1056/22/1/016301

1. Introduction

Epitaxial graphene (EG) on SiC has been taken as a potential route toward post-complementary metal-oxide semiconductor applications, which include radio-frequency, radiation-hardened electronics and a multitude of additional niche applications.[1] It is even being considered as a substitute for silicon for future micro and nano electronic device applications.[2] Up to now, most works on the fabrication of large area EG on SiC substrates have been focused on polar SiC substrates, such as SiC (0001) (Si-face SiC) and (000$\bar{1}$) (C-face SiC).[1–9] However, a tremendous difference in carrier mobility, which is always taken as one of the most important aspects to evaluate the quality of graphene, has been reported to exist between the EG on SiC and a suspended graphene, which is due to the influence of the SiC substrate on the EG.[4–7,10,11] Currently, the reported room temperature carrier mobility of EG is around 4000 cm$^2\cdot$V$^{-1}\cdot$s^{-1} on a Si-face SiC[4] and around 20000 cm$^2\cdot$V$^{-1}\cdot$s^{-1} on a C-face SiC.[5–7] However, the highest mobility of a suspended graphene sheet is extrapolated over 200000 cm$^2\cdot$V$^{-1}\cdot$s^{-1} if the carrier concentration reaches several 10^{10} cm^{-2} at 5 K,[10] and reaches 120000 cm$^2\cdot$V$^{-1}\cdot$s^{-1} at near-room temperature (240 K).[11] A crucial factor causing the carrier mobility deterioration of the graphene grown on SiC substrate is the interaction of the graphene layer with the substrate as found in the graphene grown on Si-face and C-face SiC substrates.[12] And the interaction of the graphene and SiC substrate is strong in the case of Si-face SiC, leading to an even more prominent deterioration of carrier mobility. The phenomenon enlightens us to consider the use of other orientation or nonpolar SiC substrates to mitigate the interaction and make graphene satisfy the requirements for applications. In fact, Camara *et al*. reported that a monolayer EG on SiC (11$\bar{2}$0) is strain-free and p-type with carrier mobility 2000 cm$^2\cdot$V$^{-1}\cdot$s^{-1} and carrier concentration 2×10^{12} cm^{-2} measured at liquid helium temperature.[13] They suggested that the SiC (11$\bar{2}$0) substrate can be used in fabricating large-area graphene with better electrical properties comparing to that on axis (000$\pm$1) SiC substrate. Thus, it is worthwhile carrying out more studies on EG grown on SiC (11$\bar{2}$0).

The Raman scattering allows unambiguous, high-throughput, nondestructive identification of layer numbers,[14,15] and the structural and electronic characteristics of graphene.[16–19] Especially, the temperature-dependent Raman spectrum can be used to reveal the anharmonic phonon effect of graphene reflecting total effects of thermal expansion, electron–phonon and phonon–phonon interactions, which play key roles in the electronic transport properties of a material.[20,21] Recently, the anharmonic phonon effect on EG grown on polar SiC (0001) was explored, and it is found that the action of the substrate on the EG is significant.[22] However, the nonpolar SiC substrate effect on the EG, which is

*Project supported by the National Basic Research Program of China (Grant No. 2011CB932700), the Knowledge Innovation Project of the Chinese Academy of Sciences (Grant No. KJCX2-YW-W22), and the National Natural Science Foundation of China (Grant Nos. 51072223 and 50972162).

†Corresponding author. E-mail: lwguo@iphy.ac.cn

© 2013 Chinese Physical Society and IOP Publishing Ltd

important to disclose the functions of nonpolar SiC substrate on fabricating EG with high performance, has not been studied yet. Thus, the anharmonic phonon effect of EG grown on SiC ($11\bar{2}0$) substrate is studied in order to reveal the effect of nonpolar SiC substrate on the electronic transport properties of EG.

Here, two representative samples are used to study the substrate influence on the anharmonic phonon effect through temperature-dependent Raman scattering. One sample has graphene about 8–10 graphene layers and is referred to as multilayer graphene (MLG), the other has about 2 or 3 graphene layers and is referred to as few-layer graphene (FLG) thereafter. It is found that temperature-dependent Raman lineshifts of the MLG grown on 6H-SiC ($11\bar{2}0$) behave like that of free monolayer graphene predicted by theory calculation without noticeable influence from the SiC substrate, except a little blue shift of the G and 2D peaks. This is ascribed to the isolation of the top layer graphene from the substrate by the sublayer graphene. However, the FLG shows apparent substrate influence on its temperature-dependent Raman spectra. However, the substrate effect is weak compared to that observed in the EG on 6H-SiC (0001),[22] indicating a relatively weak interaction between SiC ($11\bar{2}0$) substrate and the FLG, which renders the FLG with a high carrier mobility about 1812 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at room temperature even with a very high carrier concentration about 2.95×10^{13} cm^{-2} (p-type). Based on the G and 2D peak lineshifts of the FLG together with that of free graphene,[23] the Raman peak strain shift coefficient is deduced and compared with the reported results.

2. Experiment

The EG on 6H-SiC ($11\bar{2}0$) was fabricated through thermal annealing of SiC substrate at high temperature by using physical vapor transport (PVT) equipment. The detailed experimental process is similar to that described in our previous work;[20] the difference is that a lower growth temperature and different growth time were used for the growth of EG on 6H-SiC ($11\bar{2}0$) substrate. Here, the growth temperature was about 1350°, and the growth time was about 30 min and 15 min, respectively, for the MLG and FLG samples. Morphology images of the EGs were analyzed by atomic force microscopy (AFM). The used Raman system and the experimental process in temperature-dependent Raman experiments are the same as those used in Ref. [20].

3. Results and discussion

Figure 1 shows the Raman spectra of the MLG (in red) and the FLG (in black) on 6H-SiC ($11\bar{2}0$) measured at room temperature together with their AFM morphology images of sizes 5 μm×5 μm in the insets. The step-like AFM morphologies are ascribed to the surface features of the SiC ($11\bar{2}0$) substrates, and the EGs with wrinkles are continuously covered on the surfaces. The wrinkles are attributed to the thermal expansion coefficient (TEC) mismatch between the EG and the SiC substrate.[24] Since the intensity of the G peak is proportional to the quantity of honeycomb structural carbon atoms, the intensity ratio of the G peak to the strongest Raman peak of the SiC substrate can be used to roughly estimate the thickness of the EG grown on SiC.[25] As shown by the red curve in Fig. 1, (i) the intensity of Raman peak positioned at 1519 cm^{-1} from the SiC is very weak compared to that of the strong G peak from the MLG; (ii) the G and 2D peaks are positioned at 1583 $cm^{-1}$and 2701 cm^{-1} with full widths at half maximum (FWHMs) 19 cm^{-1} and 22 cm^{-1}, respectively, and the intensity ratio of 2D and G peaks is about 8.77 (a monolayer graphene behavior if the value is larger than 6); (iii) the lineshape of the 2D peak is highly symmetric and can be well fitted by a single Lorentz function with a small FWHM. Therefore, it is inferred that the sample referred to as MLG has about 8–10 layers. And the neighboring graphene coupling is weak in the MLG. That makes its behavior like that of a monolayer graphene, which is similar to the findings in a rotationally faulted EG on SiC ($000\bar{1}$).[5–7] The peak positions of the MLG indicate that it is slightly compressed compared with that of a free graphene since the G and 2D peaks of a free standing graphene are located around 1580 $cm^{-1}$and 2700 cm^{-1} respectively at room temperature.[20] The narrow FWHMs of the G and 2D peaks further indicate that the MLG has a high quality, which will render a high transport performance as observed in the EG on SiC ($000\bar{1}$) substrate.[5–7]

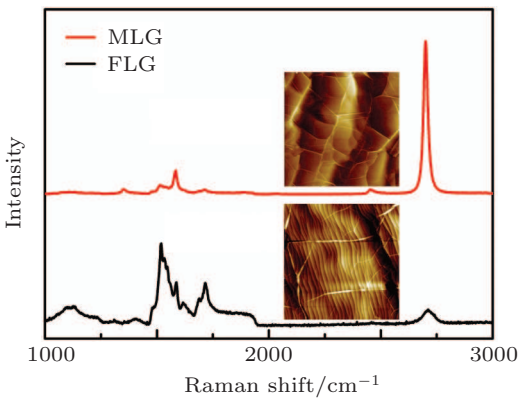


Fig. 1. (color online) Raman spectra of MLG and FLG on 6H-SiC ($11\bar{2}0$). The insets are their AFM images.

As shown by the black curve in Fig. 1, (i) the Raman peak intensity positioned at 1519 cm^{-1} from the SiC is stronger than that of the G peak from the FLG; (ii) the G and 2D peaks are positioned at 1586 $cm^{-1}$and 2713 $cm^{-1}$with FWHMs 19 cm^{-1} and 64 cm^{-1}, respectively, and the intensity ratio of 2D and G peaks is about 1.28; (iii) the shape of the 2D peak is symmetric without apparent splitting although its FWHM is wider. Thus, we infer that the graphene layer number of

the sample is about 2 or 3.[14] Meanwhile, the peak positions of the G and 2D peaks shift to high frequencies compared to those of the MLG. We believe a larger compressed strain existed in the FLG, which is different from that in the reported strain-free monolayer EG on 6H-SiC (11$\bar{2}$0).[13] The different compress strains deduced from the Raman peak positions of the FLG and the MLG hint that the strain in the MLG is inhomogeneous in different layer. Accordingly, we guess that the strain is gradually reduced from the bottom graphene near the SiC substrate to the top graphene far from the SiC substrate, although at present, we cannot perform grazing incident X-ray scattering to determine the strain in the different graphene layers of the MLG accurately. Consequently, top graphene layers of the MLG behave like free graphene. The inference is consistent with the results observed in Fig. 1.

Temperature-dependent Raman spectra were measured from 79 K to 773 K for the MLG. Figure 2 shows the temperature-dependent lineshifts of the G and 2D peaks, where $\Delta\omega_{\rm G} = \omega_{\rm G} - \omega_{\rm G0}$, $\Delta\omega_{\rm 2D} = \omega_{\rm 2D} - \omega_{\rm 2D0}$, $\omega_{\rm G0}$ and $\omega_{\rm 2D0}$ are the peak positions of the G and 2D peaks at a temperature close to 0 K. Here, $\omega_{\rm G0}$ and $\omega_{\rm 2D0}$ are taken to be 1584.5 cm^{-1}and 2706 cm^{-1} respectively to fit the experimental data. In Fig. 2(a), the solid red line shows the G peak variation with temperature predicted by a theoretical calculation for a free graphene,[23] which has been confirmed by our previous experiments.[20] In Fig. 2(b), the solid red line is a Klemens model fitting to the experimental results of temperature-dependent Raman lineshifts of the 2D peak of a free standing graphene, considering contributions of 3-phonon and 4-phonon interactions.[20] From Figs. 2(a) and 2(b), it is seen that the experimental results of the MLG well match the calculation results of a free graphene, indicating that the MLG behaves like a free graphene without the influence of the substrate being observed, except a little shift of peak positions of the G and 2D peaks. We attribute this phenomenon to the isolation of the upper graphene layers from the SiC substrate by the bottom graphene layers next to the substrate, which makes the upper graphene layers behave like a free graphene.

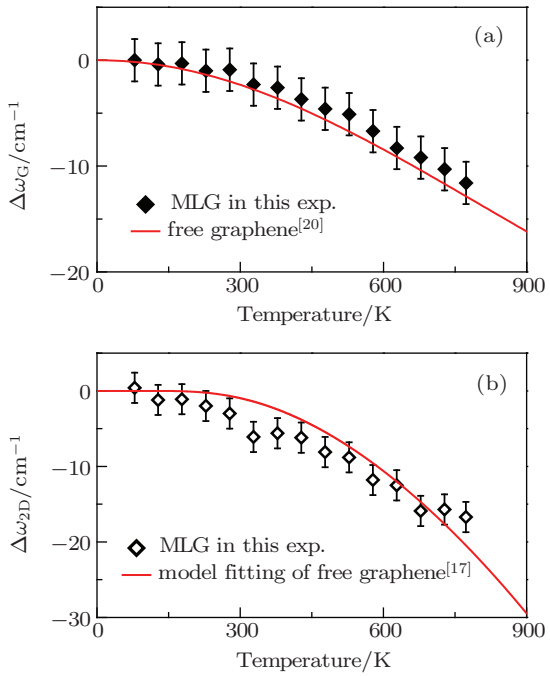


Fig. 2. (color online) Temperature-dependent lineshift of the (a) G and (b) 2D peaks of the MLG, where an error bar is drawn in length of 2 cm^{-1}. In panel (a), the red line is the result of free graphene.[23] In panel (b), the red line is a model fitting to the experimental results.[20]

Figures 3(a) and 3(b) show the temperature dependences of the Raman G and 2D peak lineshifts of the FLG, respectively, measured in the temperature range from 159 K to 773 K, where $\Delta\omega_{\rm G} = \omega_{\rm G} - \omega_{\rm G0}$, $\Delta\omega_{\rm 2D} = \omega_{\rm 2D} - \omega_{\rm 2D0}$, $\omega_{\rm G0}$ and $\omega_{\rm 2D0}$ are the peak positions of the G and 2D peaks at a temperature close to 0 K, respectively. Here, $\omega_{\rm G0}$ and $\omega_{\rm 2D0}$ are taken as 1589.4 cm^{-1} and 2714 cm^{-1} respectively to fit our experimental data. In Fig. 3, the red lines are the same to those in Fig. 2, and the black lines are fitting to our experimental data. In Fig. 3(a), it is seen that different from the MLG, the lineshift of the G peak is deviated from that of the free graphene. We attribute this divergence to the substrate influence on the anharmonic phonon effect in the FLG. In fact, the anharmonic phonon effect of the EG on SiC (0001) has been reported, and a linear G peak lineshift rate was found to be -0.043 cm^{-1}/K in the temperature range from 300 K to 400 K.[22] However, our FLG shows a linear lineshift rate about -0.016 cm^{-1}/K in the temperature range from 300 K to 400 K and -0.038 cm^{-1}/K from 543 K to 743 K. The linear lineshift rate of our FLG is almost one third of that of the EG on SiC (0001) in the temperature range from 300 K to 400 K.[22] This indicates that the SiC (11$\bar{2}$0) substrate effect on the FLG is much weaker compared with that observed in the EG grown on SiC (0001). Since the deterioration of carrier mobility of the EG on SiC substrate is mainly attributed to the interaction of graphene layers with the substrate as found in graphenes grown on Si-face and C-face SiC substrates,[12] the weak interaction between the FLG and 6H-SiC (11$\bar{2}$0) will introduce a weak interference on the intrinsic physical properties of graphene compared with that of EG on SiC (0001). This renders the FLG a high carrier mobility around 1812 cm$^2\cdot$V$^{-1}\cdot$s^{-1} at room temperature, even with a very high carrier concentration about 2.95×10^{13} cm^{-2} (p-type). Similarly, as shown in Fig. 3(b), the lineshift of the 2D peak of the FLG is even more seriously deviated from that of the free standing graphene,[20] which is also ascribed to the substrate influence on the anharmonic phonon effect of EG. The reason will be discussed below.

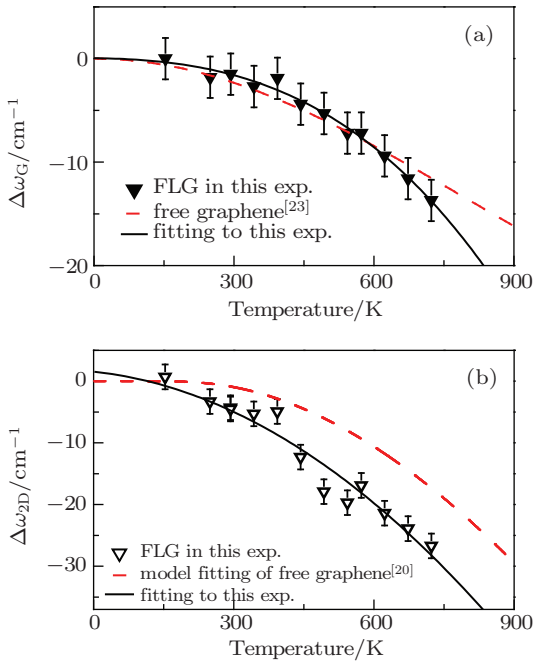


Fig. 3. (color online) Temperature-dependent Raman lineshifts of the (a) G and (b) 2D peaks of the FLG, where an error bar is drawn in length of 2 cm^{-1}. The red lines are the same to those in Fig. 2, and the black lines are fitting to our experimental data.

Usually, the substrate influence on the EG is mainly reflected in two aspects: charge doping and inducing strain due to the TEC mismatch. The charge doping can be qualitatively drawn out from an integrated intensity ratio of 2D and G peaks (I_{2D}/I_G), because it is sensitive to the carrier concentration.[17] Thus, the temperature dependence of I_{2D}/I_G for the FLG is studied, as shown in Fig. 4. It is seen that I_{2D}/I_G linearly changes from 3.3 to 1.5 in the temperature range from 159 K to 773 K. According to Ref. [17], the changes of I_{2D}/I_G from 3.3 to 1.5 induced by the charge doping will bring measly 1–2 cm^{-1} lineshift in the G peak. Thus, charge doping is ruled out to be a dominant factor in the substrate effect.

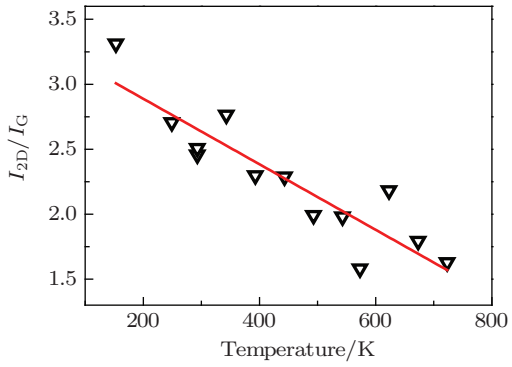


Fig. 4. (color online) Temperature dependence of intensity ratio I_{2D}/I_G of 2D and G peaks of the FLG.

To explore the primary mechanism, the calculation of relationship between temperature and strain caused by the TEC mismatch between the EG and 6H-SiC is performed.

Since the charge doping effect from substrate has been ruled out as being a dominant factor in the substrate effect, the effect of strain induced by the TEC mismatch should be the governing mechanism. Thus, the Raman lineshift of the FLG can be considered to result from the strain effect and the thermal effect of a free graphene, that is, $\Delta\omega(T) = \Delta\omega^{\text{free}}(T) + \Delta\omega^{\text{substrate}}(T)$, and $\Delta\omega^{\text{substrate}}(T) \approx \Delta\omega^{\text{strain}}(T)$, where $\Delta\omega(T)$ is the Raman frequency shift of the G or 2D peak, $\Delta\omega^{\text{free}}(T)$ is the Raman frequency shift of a free graphene, which can be attributed to lattice thermal expansion and the anharmonic effect due to the phonon self-energy.[23] The $\Delta\omega^{\text{substrate}}(T)$ is the substrate effect on the anharmonic phonon effect of the FLG, and $\Delta\omega^{\text{strain}}(T)$ is the induced strain effect due to the TEC mismatch between the FLG and the SiC substrate. If we assume that the FLG is pinned on the 6H-SiC (11$\bar{2}$0) without slipping relative to the supporting substrate, $\Delta\omega^{\text{strain}}(T)$ can be expressed as[26]

$$\Delta\omega^{\text{strain}}(T) = \beta\varepsilon(T) = \beta\int_{297\ \text{K}}^{T}(\alpha_{\text{SiC}}(T) - \alpha_{\text{grphene}}(T))\,\mathrm{d}T,$$

where β is the Raman peak strain shift coefficient, and α_{SiC} and α_{graphene} are the temperature-dependent TECs of SiC and graphene, respectively. The TECs of SiC are taken from a well recognized TEC of an undoped 6H-SiC,[27] whose TECs $\alpha_{\text{a-SiC}}$ along a-direction and $\alpha_{\text{c-SiC}}$ along c-direction are shown in Fig. 5(a) with red-dashed and blue dot-dashed lines, respectively. The TEC of graphene is replaced by that of graphite to simplify the calculation.[28] Although the SiC substrate used in our experiment is a semi-insulated 6H-SiC (11$\bar{2}$0), the difference of SiC TEC induced by the little difference in conductivity is ignorable. In Fig. 5(a), it is seen that α_{graphite} is negative in the temperature range from 4 K to 900 K. Meanwhile, it is noted that the TECs of $\alpha_{\text{a-SiC}}$ and $\alpha_{\text{c-SiC}}$ are nearly the same within 10^{-7} K^{-1}. To simplify our calculation of $\Delta\omega^{\text{strain}}(T)$, $\alpha_{\text{c-SiC}}$ is used as the TEC of 6H-SiC (11$\bar{2}$0), which gives a maximum TEC difference between SiC and graphene. Therefore, the resulting strain is effectively available for EG on other polar hexagonal structure SiC substrate. Under the above hypothesis, the strain induced by TEC mismatch as a function of temperature can be depicted in Fig. 5(b), where a zero strain state is set at 297 K. In fact, the FLG on 6H-SiC (11$\bar{2}$0) sustains little compression strain at room temperature as discussed above. Although the relative change value of the calculated strain is positive in the temperature range from 297 K to 900 K as shown in Fig. 5(b), the realistic strain variation process is gradually releasing the initial compression strain to zero and then bearing a tension strain induced by the TEC difference during the temperature change from 297 K to 900 K. In Fig. 5(b), it is seen that the strain caused by the TEC mismatch can reach 0.35% at 900 K relative to that at 4 K, which is slightly larger than that of graphene on SiO_2 due to a relative smaller TEC mismatch between graphene and SiO_2.[26] Figures 5(c) and 5(d) give the estimated Raman frequency shifts of the G and 2D peaks induced by the strain existed in the FLG due to the SiC substrate

effect, together with the model calculations adopting the reported different strain shift coefficients β for the G and 2D peaks.[26,29–36] Since the reported strain shift coefficients scatter a lot ranging from -12.5 cm^{-1}/% to -70 cm^{-1}/% for the G peak and from -7.8 cm^{-1}/% to -164 cm^{-1}/% for the 2D peak,[26,29–36] only a few are adopted to fit our experimental results as shown in Figs. 5(c) and 5(d). It is found that the best fitting parameters are $\beta_{\rm G}$ among -14.2 cm^{-1}/% to -31.3 cm^{-1}/% for the G peak and $\beta_{\rm 2D}$ among -61 cm^{-1}/% to -64 cm^{-1}/% for the 2D peak. The values of $\beta_{\rm G}$ and $\beta_{\rm 2D}$ deduced here are consistent with the results found in a graphene located on a flexible substrate under uniaxial stress.[29–31] The results illustrate that there is no apparent extra SiC substrate effect on the graphene besides the TEC mismatch effect. The conclusion suggests that the SiC (11$\bar{2}$0) is a potential substrate for growing high quality graphene with a weak substrate effect.

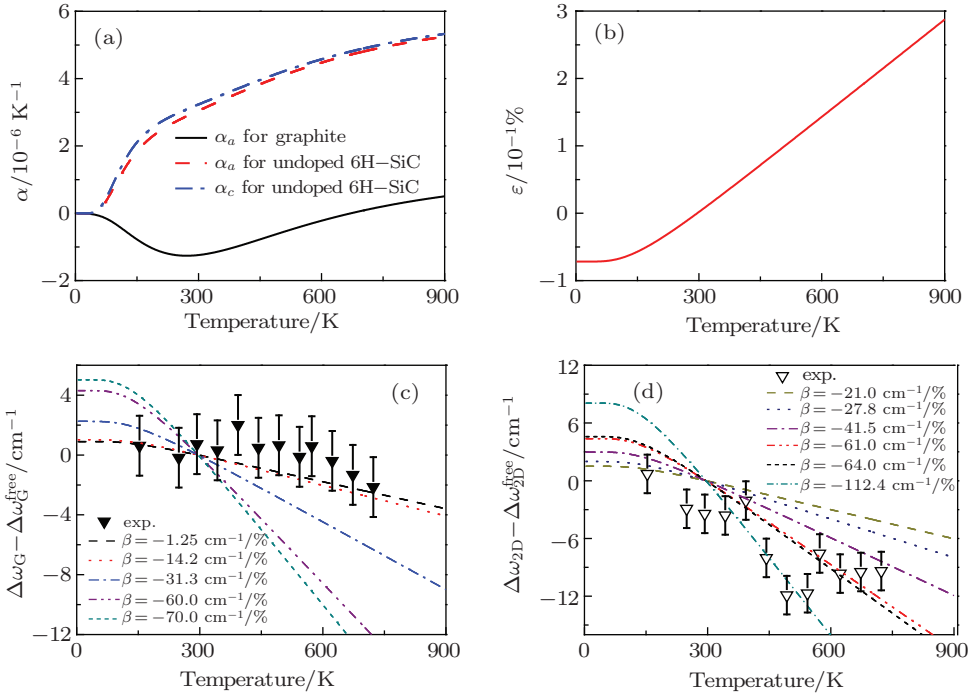


Fig. 5. (color online) (a) TEC of undoped 6H-SiC along *a*- (α_a) and *c*-directions (α_c),[27] and the calculated TEC in basal plane *a*-direction for graphite.[28] (b) Temperature-dependent strain ε in EG due to the TEC mismatch. Panels (c) and (d) show the strain induced G and 2D peak Raman lineshifts of the FLG, respectively, where color solid lines are model fittings adopting different strain coefficients β reported.

4. Conclusion

The substrate influence on the Raman peak lineshifts of EG on 6H-SiC (11$\bar{2}$0) is investigated based on temperature-dependent Raman scattering. It is found that the Raman lineshifts of the MLG are consistent with that of a free graphene without noticeable effect from the SiC substrate due to the isolation function of bottom layer graphene, which suggests that the MLG is similar to the EG on C-face SiC. While the Raman lineshifts of the FLG on 6H-SiC (11$\bar{2}$0) are offset from that of a free graphene, and the deviations are determined by the strain shift coefficient and the TEC mismatch between the FLG and SiC. It is found that the substrate effect on the FLG on SiC (11$\bar{2}$0) is much weaker as compared with that observed in the EG on 6H-SiC (0001). The strain shift coefficients $\beta_{\rm G}$ and $\beta_{\rm 2D}$ induced by the substrate effect are deduced and found to be consistent with those in a situation with an uniaxial stress on a graphene on a flexible substrate. The relative weak influence from the SiC (11$\bar{2}$0) substrate renders the FLG a high carrier mobility around 1812 cm$^2\cdot$V$^{-1}\cdot$s^{-1} at room temperature even with a very high carrier concentration about 2.95×10^{13} cm^{-2}, which indicates that the nonpolar SiC (11$\bar{2}$0) substrate opens a new route for fabricating EG with high performance.

References

[1] Robinson J, Weng X, Trumbull K, Cavalero R, Wetherington M, Frantz E, LaBella M, Hughes Z, Fanton M and Snyder D 2009 *ACS Nano* **4** 153
[2] Emtsev K V, Bostwick A, Horn K, Jobst J, Kellogg G L, Ley L, McChesney J L, Ohta T, Reshanov S A and Röhrl J 2009 *Nature Mater.* **8** 203
[3] Virojanadara C, Syväjarvi M, Yakimova R, Johansson L, Zakharov A and Balasubramanian T 2008 *Phys. Rev.* B **78** 245403
[4] Lin Y M, Dimitrakopoulos C, Jenkins K A, Farmer D B, Chiu H Y, Grill A and Avouris P 2010 *Science* **327** 662
[5] Lin Y M, Dimitrakopoulos C, Farmer D B, Han S J, Wu Y Q, Zhu W J, Gaskill D K, Tedesco J L, Myers-Ward R L, Eddy C R, Grill A and Avouris P 2010 *Appl. Phys. Lett.* **97** 112107
[6] Jernigan G, VanMil B, Tedesco J, Tischler J, Glaser E, Davidson III A, Campbell P and Gaskill D 2009 *Nano Lett.* **9** 2605
[7] Robinson J, Wetherington M, Tedesco J, Campbell P, Weng X, Stitt J, Fanton M, Frantz E, Snyder D and VanMil B 2009 *Nano Lett.* **9** 2873

[8] Wang D C, Zhang Yu M, Zhang Y M, Lei T M, Guo H, Wang Y H, Tang X Y and Wang H 2012 *Chin. Phys.* B **21** 038102
[9] Hao X, Chen Y F, Li P J, Wang Z C, Liu J B, He J R, Fan R, Sun J R, Zhang W L and Li Y R 2012 *Chin. Phys.* B **21** 046801
[10] Bolotin K I, Sikes K, Jiang Z, Klima M, Fudenberg G, Hone J, Kim P and Stormer H 2008 *Sol. St. Comm.* **146** 351
[11] Bolotin K, Sikes K, Hone J, Stormer H and Kim P 2008 *Phys. Rev. Lett.* **101** 96802
[12] Chen W, Chen S, Ni Z, Huang H, Qi D, Gao X, Shen Z and Wee A 2010 *Jpn. J. Appl. Phys* **49** 3
[13] Camara N, Jouault B, Caboni A, Tiberj A, Godignon P and Camassel J 2011 *Nanosci. Nanotech. Lett.* **3** 49
[14] Lee D, Riedl C, Krauss B, Von Klitzing K, Starke U and Smet J 2008 *Nano Lett.* **8** 4320
[15] Graf D, Molitor F, Ensslin K, Stampfer C, Jungen A, Hierold C and Wirtz L 2007 *Nano Lett.* **7** 238
[16] Ferrari A, Meyer J, Scardaci V, Casiraghi C, Lazzeri M, Mauri F, Piscanec S, Jiang D, Novoselov K and Roth S 2006 *Phys. Rev. Lett.* **97** 187401
[17] Das A, Pisana S, Chakraborty B, Piscanec S, Saha S, Waghmare U, Novoselov K, Krishnamurthy H, Geim A and Ferrari A 2008 *Nature Nanotech.* **3** 210
[18] Yang R, Shi Z W, Zhang L C, Shi D X and Zhang G Y 2011 *Nano Lett.* **11** 4083
[19] Wang D C, Zhang Y M, Zhang Y M, Lei T M, Guo H, Wang Y H, Tang X Y and Wang H 2011 *Chin. Phys.* B 20 128101
[20] Lin J, Guo L, Huang Q, Jia Y, Li K, Lai X and Chen X 2011 *Phys. Rev.* B **83** 125430
[21] Bonini N, Rao R, Rao A M, Marzari N and Menéndez J 2008 *Phys. Stat. Sol.* B **245** 2149
[22] Ferralis N, Maboudian R and Carraro C 2011 *Phys. Rev.* B **12** 081410(R)
[23] Bonini N, Lazzeri M, Marzari N and Mauri F 2007 *Phys. Rev. Lett.* **99** 176802
[24] Ferralis N, Maboudian R and Carraro C 2008 *Phys. Rev. Lett.* **101** 156801
[25] Ni Z, Chen W, Fan X, Kuo J, Yu T, Wee A and Shen Z 2008 *Phys. Rev.* B **77** 115416
[26] Yoon D, Son Y W and Cheong H 2011 *Nano Lett.* **8** 3227
[27] Stockmeier M, Muller R, Sakwe S, Wellmann P and Magerl A 2009 *J. Appl. Phys.* **105** 033511
[28] Tsang D, Marsden B, Fok S and Hall G 2005 *Carbon* **43** 2902
[29] Huang M, Yan H, Chen C, Song D, Heinz T F and Hone J 2009 *Proc. Nat. Acad. Sci. USA* **106** 7304
[30] Ni Z H, Yu T, Lu Y H, Wang Y Y, Feng Y P and Shen Z X 2008 *ACS Nano* **2** 2301
[31] Frank O, Bousa M, Riaz I, Jalil R, Novoselov K S, Tsoukleri G, Parthenios J, Kavan L, Papagelis K and Galiotis C 2012 *Nano Lett.* **2** 687
[32] Ding F, Ji H, Chen Y, Herklotz A, Dörr K, Mei Y, Rastelli A and Schmidt O G 2010 *Nano Lett.* **9** 3453
[33] Gong L, Kinloch I A, Young R J, Riaz I, Jalil R and Novoselov K S 2010 *Adv. Mater.* **22** 2694
[34] Yu T, Ni Z, Du C, You Y, Wang Y and Shen Z 2008 *J. Phys. Chem. C.* **112** 12602
[35] Young R J, Gong L, Kinloch I, Riaz I, Jalil R and Novoselov K 2011 *ACS Nano* **4** 3079
[36] Tsoukleri G, Parthenios J, Papagelis K, Jalil R, Ferrari A C, Geim A K, Novoselov K S and Galiotis C 2009 *Small* **5** 2397