Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp125-126

TEM characterization of epitaxial graphene formed on Si(111), Si(110), Si(100)

Hiroyuki Handa[1], Ryota Takahashi[1], Shunsuke Abe[1], Kei Imaizumi[1], Myung-Ho Jung[1], Shun Ito[2], Hirokazu Fukidome[1] and Maki Suemitsu[1, 3]

[1] Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan
[2] Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
[3] CREST, Japan Science and Technology Agency, Tokyo 102-0075, Japan
Phone: +81-22-217-5484, E-mail: handa88@riec.tohoku.ac.jp

1. Introduction

In 2004, formation of graphene, a two-dimensional honeycomb network of sp^2-bonded carbon atoms, was reported by Novoselov and Geim *et al* [1]. Ever since, various marvelous properties of graphene, like electron mobility of 200,000 cm^2/Vs or more [2], have evoked ever-increasing numbers of papers on this emerging research material.

Among various methods for forming graphene, the mechanical exfoliation (peeling) method [1] and the epitaxial graphene method using SiC substrates [3] have been most common. Unlike the former with the trial-and-error nature, the epitaxial graphene method has higher adaptability to industry [4]. Its promising properties as a channel material have also recently been demonstrated, as evidenced by the demonstration of a field effect transistor with a cut-off frequency of 100 GHz [5]. The epitaxial graphene method, however, still suffers from limitations in adaptability to industry because of the limited diameter and the high price of the available SiC substrates. In this context, authors have succeeded in forming graphene on a thin SiC film grown on a large-diameter Si wafer [6-8]. The graphene-on-silicon technology, or GOS, may have tremendous impacts on introducing graphene into Si technology. In GOS, graphene forms on a 3C-SiC thin film grown on a Si substrate, by annealing the SiC film in UHV at 1250ºC or higher. To our surprise, graphene grows on three major low-index planes of Si(111), (110) and (100), despite their different crystallographic orientations [9]. However, direct observation of the GOS structure, say by using transmission-electron microscopy (TEM), has been limited up to now. It is especially important to investigate the impacts of Si surface orientation on the structural properties of GOS. In this paper, we have conducted cross-sectional TEM measurements on GOS, focusing on the surface orientational dependence.

2. Experimental

The 3C-SiC fim used in GOS has been grown with gas-source molecular-beam-epitaxy (GSMBE) using monomethyl-silane (MMS) as a single source. Details of the apparatus are described in Ref. [10]. Samples are B-doped, *p*-type Si(111), Si(110) and Si(100) wafer, cut to 7×40 mm^2 size. After an *ex-situ* wet cleaning, they were transferred to the chamber, in which they were degassed, and flash-annealed at 1200°C for several times to yield a clean surface. Sample heating was conducted by a resistive heating. After the *in-situ* cleaning, MMS was introduced to the chamber via leak valve at a pressure of 4.0×10^{-2} Pa. Growth experiment consists of two stages: a buffer-layer formation conducted at 600°C for 5 min and a subsequent SiC growth at 1050°C for 60 min. For this growth condition, the film thickness is typically 100 nm as we evaluate with a TEM. After the growth, MMS was evacuated from the chamber, and the sample was annealed in vacuum at 1250ºC for 30 min. The sample was evaluated by Raman-scattering spectroscopy (Ar 514 nm) and TEM.

3. Results and Discussion

Figure 1 shows XRD patterns of SiC films grown on Si substrates. It indicates formation of SiC(111), SiC(110), and SiC(100) films on Si(111), Si(110) and Si(100) faces, respectively. Raman scattering spectra of the annealed SiC/Si substrates (Fig. 2) all indicate successful formation of graphene on the three surfaces, as evidenced by the well defined G and G' peaks. This finding, i.e., equally successful growth of graphene on three major low-index Si (SiC) faces, may have great impacts academically and technologically on the future of graphene. The latter includes the possibility of forming 3D-shaped graphene devices on Si substrates. From XPS-C1s measurement, the electronic character of GOS is shown to change depending on the orientation, from the semiconductor nature on (111) to the metallic nature on (110) and (100) faces [9]. Cross-sectional TEM images of graphene on Si(111), Si(110) and Si(100) substrates are shown in Fig. 3. The graphitization condition is the same for the three orientations: 1250 ºC for 30 min. The number of graphene layers are shown to strongly depend on the orientation, which varies in the order of Si(110) > (100) > (111). In contrast, the quality of graphene, as judged by Raman-scattering spectroscopy, is not so much affected by the orientation. Investigations on the growth kinetics of GOS are now under way.

4. Conclusions

In summary, we have succeeded in forming graphene on a 3C-SiC thin film, which is prepared by heteroepitaxy of 3C-SiC on Si(111), Si(110) and Si(100) substrate. This

technology can be of enormous importance in realizing graphene-based devices on Si substrate.

Acknowledgements

The work was supported by CREST, the Japan Science and Technology Agency (JST), Japan.

References

[1] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, A. A. Firsov, Science **306** (2004) 666.

[2] S. V. Morozov, K. S. Novoselov, M. I. Katsnelson, F. Schedin, D. C. Elias, J. A. Jaszczak, A. K. Geim, Phys. Rev. Lett. **100** (2008) 016602.

[3] E. Rollings, G. -H. Gweon, S. Y. Zhou, B. S. Mun, J. L. Mc-Chesney, B. S. Hussain, A. V. Fedorov, P. N. First, W. A. de Heer, A. Lanzara, J. Phys. Chem. Solids **67** (2006) 2172.

[4] P. Sutter, Nature Mater. **8** (2009) 171.

[5] Y. -M. Lin, C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H. -Y. Chiu, A. Grill, Ph. Avouris, Science **327** (2010) 662.

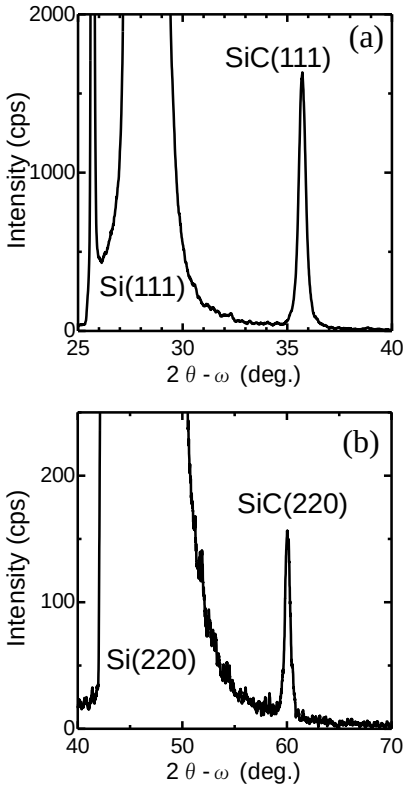
[6] M. Suemitsu, Y. Miyamoto, H. Handa, A. Konno, e-J. Surf. Sci. Nanotech. **7** (2009) 311.

[7] Y. Miyamoto, H. Handa, E. Saito, A. Konno, Y. Narita, M. Suemitsu, H. Fukidome, T. Ito, K. Yasui, H. Nakazawa, T. Endoh, e-J. Surf. Sci. Nanotech. **7** (2009) 107.

[8] H. Fukidome, Y. Miyamoto, H. Handa, E. Saito, M. Suemitsu, Jpn. J. Appl. Phys. **49** (2010) 01AH03.

[9] H. Fukidome, R. Takahashi, Y. Miyamoto, H. Handa, H. -C. Kang, H. Karasawa, T. Suemitsu, T. Otsuji, A. Yoshigoe, Y. Teraoka, M. Suemitsu, arXiv: 1001. 4955 (2010).

[10] H. Nakazawa, M. Suemitsu, J. Appl. Phys. **93** (2003) 5282.



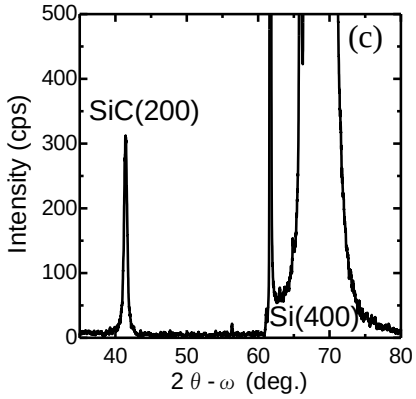


Fig. 1 XRD spectra (Out-of-plane) of 3C-SiC thin film on (a) Si(111), (b) Si(110) and (c) Si(100) substrates.

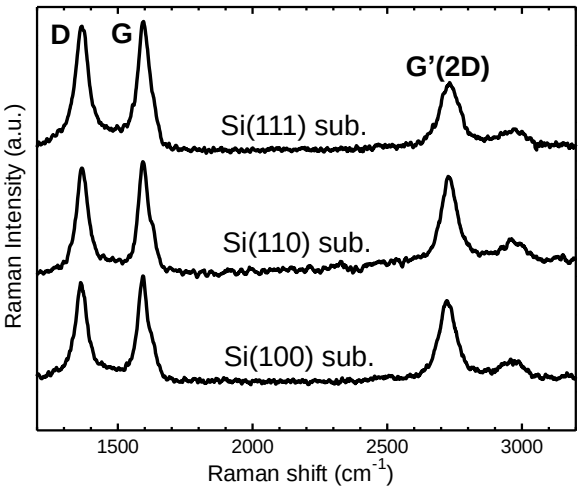


Fig. 2 Raman spectra of graphene on Si(111), Si(110) and Si(100) substrates.

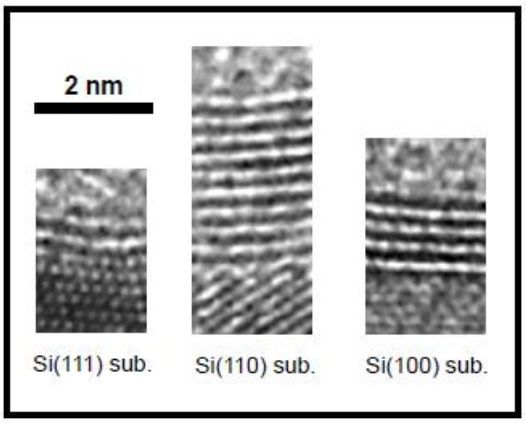


Fig. 3 Cross-sectional TEM images of graphene on Si(111), Si(110) and Si(100) substrates.