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Epitaxy of Graphene on Si substrates toward Three-Dimensional Graphene Devices

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1. Introduction

Graphene, a two-dimensional sp^2 network of carbon atoms, is now viewed as one of the most promising materials to realize *beyond-CMOS* technology [1]. A major challenge for graphene to play this role, however, is a lack of reasonable process that allows epitaxial growth of graphene on suitable substrates. Now-prevailing methods, such as exfoliation from graphite and epitaxy of graphene on SiC bulk crystals, are not adequate for mass production of devices, where Si substrate is a prerequisite.

In this context, we are trying to develop new graphene technologies that are compatible to the existing silicon technology. As the first step, we have succeeded in the epitaxy of graphene on Si substrates [2-4]. This *graphene on silicon* (GOS) film grows two-dimensionally on Si wafers for a large area (> 3 cm^2), which is crucial as a planar technology. Our GOS film has been applied to a channel layer for a field effect transistor (FET), whose successful performance is presented also in this conference [5].

As the second step, we are now seeking a way to develop a three-dimensional GOS (3D-GOS) process to match the recent demands from the silicon technology. Today, Si devices are about to employ 3D structures such as multi-gated FETs, in which not only Si(100) but also Si(110) faces are utilized as the channel layer [6]. To extend this trend toward 3D-GOS, a technology that allows formation of epitaxial graphene on various low-index orientations of Si, such as (100), (111), and (110), would definitely be beneficial. In this late news, we report successful epitaxy of graphene on Si(100), Si(111) and Si(110) faces.

2. Experimental

GOS process consists of a pair of sequential steps [2-4]. First, a SiC thin film is epitaxially grown on silicon substrates. A gas-source molecular beam epitaxy, using monomethylsilane as the single source, is employed. A typical thickness of the SiC film is 80 nm. Second, the surface of the SiC thin film is thermally graphitized by annealing at > 1400 K. During the annealing, the Si sublimation converts the surface area into graphene.

The characterization of the GOS film is mainly conducted by Raman spectroscopy, in which the 2D network of sp^2 carbon atoms is detected [7]. Transmission electron microscopy (TEM) is also used to characterize the layered structure of the GOS.

3. Results and Discussions

Figure 1 shows the optical micrographs of graphene formed on Si(110). As one can see in the left, The graphene uniformly covers the 7 × 40 mm^2 sample.

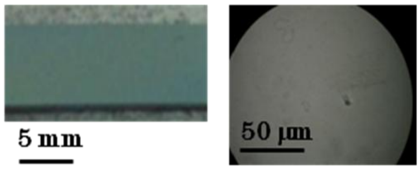

Fig. 1. Appearance (left) and an optical micrographs (right) of the graphene formed on Si(110).

Figure 2 shows the Raman spectra of the bare (lower) and the graphitized (upper) SiC thin film on Si(110). Graphitization was conducted at 1473 K. The characteristic peaks of graphene [7], D, G and G' bands, are clearly seen in the graphitized sample, in sharp contrast to the bare SiC/Si(110). The presence of G and G' bands indicates the formation of the network of sp^2 carbon atoms.

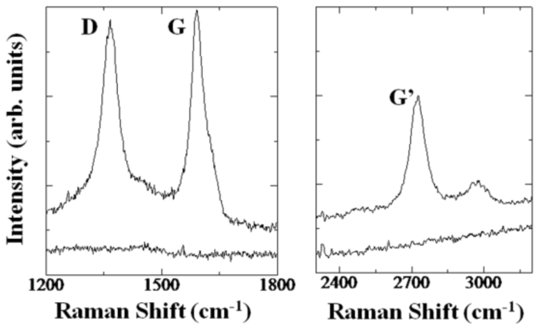

Fig. 2 Raman spectra of the bare (lower) and the graphitized (upper) SiC films on Si(110).

In addition to the Raman spectroscopic confirmation shown above, TEM images clearly demonstrate a planar structure of the graphene film as well (Fig. 3). It is therefore unambiguously concluded that a graphene film is successfully formed in a planar shape on silicon substrates via a thermal graphitization of the epitaxial SiC thin film.

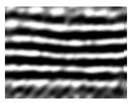

Fig. 3 Cross-sectional TEM image of graphene on Si(110).

Comparison of three different Si faces is shown in Fig. 4. All the Raman spectra of the graphitized SiC/Si films indicate successful formation of graphene on these Si(110), Si(100) and Si(111) faces. Separate XRD measurements indicate formation of SiC(110)+SiC(111), SiC(100), and SiC(111) films on these Si(110), Si(100) and Si(111) faces, respectively. This equally successful growth of graphene on these Si (SiC) faces, despite their different crystallographical symmetry, is therefore remarkable. Investigations on the growth kinetics of GOS are now under way. Practically, however, this observation clearly demonstrates that graphene films can be formed on any major low-indexed silicon substrates, which leads us to the possibility of forming 3D-shaped graphene and its devices on Si substrates.

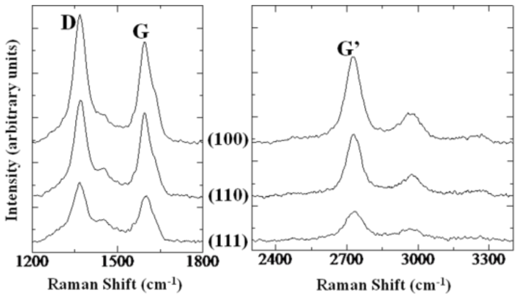

Fig. 4 Raman spectra of graphene on Si(111), Si(110) and Si(100) substrates formed by graphitization of the SiC thin films on these surfaces.

4. Conclusions

Large-area GOS films can be formed on any silicon substrates with major low-index orientations: (111), (100) and (110). This result is quite promising in realizing 3D-GOS on microstructured silicon substrates. This is a unique feature of the GOS process that can hardly be achieved by any other methods of graphene production.

Acknowledgements

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