Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1296-1297

Electric-field-induced band gap of bilayer graphene in ionic liquid

Yusuke Yamashiro, Yasuhide Ohno, Kenzo Maehashi, Koichi Inoue and Kazuhiko Matsumoto

The Institute of Scientific and Industrial Research, Osaka University,
8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
Phone/Fax: +81-6-6879-8412
E-mail: yamash11@sanken.osaka-u.ac.jp

1. Introduction

Graphene is formed by a single layer of carbon atoms. Excellent properties such as a massless carrier make graphene one of the most interesting candidates for studying material physics.[1)] Additionally for their extraordinary high mobility, graphene is expected to be a new material for building blocks of logic circuits and sensors. However, graphene field-effect transistors (GFETs) don't have off-states owing to the lack of a band gap. Graphene nano-ribbons have been investigated to generate the band gap in graphene although it is technologically difficult to fabricate graphene nano-ribbon within a tolerance of a few nanometer. Alternatively, the band gap can be generated with applying a perpendicular electric field in the bilayer graphene.[2-4)] The method does not need to etch or cut graphene. The electric field is generally applied across insulators with top-gate and back-gate electrodes with controlling the potential of graphene layers. In this study, we applied an electric field to graphene using an ionic-liquid gate instead of a top gate electrode and an insulator. The ionic-liquid gate can apply effective electric fields than other type of the gates because of its large capacitance.

2. Experimental

Figure 1 shows a schematic diagram of experimental setup. In this study, graphene layers were extracted from kish graphite by a mechanical exfoliation and were put on highly *n*-doped Si substrates covered with a 300-nm-thick SiO_2 layer. The *n*-doped Si wafer was used as a back-gate electrode. Ti/Au (2 nm/ 40 nm) source, drain and side-gate electrodes were formed by a photolithography, a metal deposition and a lift-off technique. The channel length and the width of graphene are approximately 3 μm and 3-5 μm, respectively. The side-gate electrodes were patterned approximately 20 μm away from the channels. After the devices were annealed at 300 °C for one hour in hydrogen atmosphere to clean the surface of graphene layers, ionic liquids (DEME-TFSI) were used onto the graphene channel and the side-gate electrode without any passivation films. The samples were annealed again in vacuum at 150 °C to dehydrate the ionic liquid before every measurement of electrical characteristics because the dewatered ionic liquids have a large electrical strength (3.0 − 3.5 V).

3. Results and discussion

Figure 2 shows the resistance (R) in the GFET as a function of the back-gate voltage (V_{bg}) and the side-gate voltage (V_{sg}) mesured at a drain voltage (V_d) of 5 mV and a temperature of 300 K in vacuum. The inset is an extended figure of the resistance against the side gate. Ambipolor behaviors were observed in both back-gate plots and side-gate plots, although the magnitude of these transconductances was obviously different, indicating that the electrical double layer working as a very thin insulator was formed in the surface of graphene using the side gate in the ionic liquid.

Figure 3 (a) shows the resistance contour plots as a function of the back- and side-gate voltages of monolayer and bilayer graphene. In each plots, ridge lines meaning charge neutrality were clearly observed (indicated dashed line). The magnitude of the double layer capacitance, which was estimated from the slope of dashed line in Fig. 3 (a), is approximately 200 times larger than that of 300-nm-thick SiO_2 layer. The thickness of the electrical double layer (d_{edl}) was given by the slope and parallel plate approximation.

$$\frac{C_{sg}}{C_{bg}} = \frac{\varepsilon_{il} d_{SiO2}}{\varepsilon_{SiO2} d_{edl}} = 200$$

where, C_{sg}, C_{bg}, ε_{il} and ε_{SiO2} are capacitances of the electrical double layer, the capacitance of SiO_2 layer, the relative permittivity of ionic liquid and that of SiO_2, respectively. For ε_{il} = 10, ε_{SiO2} = 4, d_{SiO2} = 300 nm and C_{sg}/ C_{bg} = 200, d_{edl} is estimated to be 3.75 nm. A thickness of the electrical double layer was reported to be a few nanometer. Therefore, our calculated value is consistent with other reports.

The resistance contour plots in Fig. 3(a) reveal that the bilayer GFET has different properties from the monolayer GFET. One peak was observed in the resistance of monolayer GFET, however, two high resistance regions were observed for the bilayer GFET (near A and C). Figure 3 (b) shows the resistances plotted against the electric field for monolayer, bilayer and trilayer GFETs at 300 K. The resistances were obtained at the Dirac points of the GFETs. These curves are normalized to the resistance at electric field of 0 V/nm. The points of A, B, and C in Fig. 3(b) correspond to those in Fig. 3(a). The increases in the resistance were observed with increasing the magnitude of the electric field in the bilayer GFET. On the other hand, the decreasing resistances were observed for the monolayer and trilayer GFETs. The results indicate that a band gap was induced in the ionic-liquid gated bilayer GFET by electric field.

We investigated temperature dependence of a conductance to derive the value of the band gap with four-probe method in bilayer graphene. Figure 4 shows the electric field dependence of the band gap, which is given by Arrhenius plots of the conductance (shown inset). The band gap was given by the slope of a fitted line, indicating that the band gap was estimated to be 260 meV at the electric field of 3.0 V/nm, which corresponds to the side- and back-gate voltages of -3.0 and 60 V, respectively. Therefore, the ionic-liquid gate applied effective electric fields to generate the band gap in the bilayer GFETs.

4. Conclusions

We investigated the transfer characteristics in the ionic-liquid-gate bilayer GFETs. The electrical double layer in the ionic-liquid has 200 times larger capacitance than a 300-nm-thick SiO_2 layer, resulting in the effective electric fields. Electrical measurements in the bilayer GFET indicated the monotonic increases in resistance with increasing magnitude of electric field, resulting from the generation of the band gap in bilayer graphene. The band gap of 260 meV was obtained at the side- and back-gate voltages of -3.0 and 60 V.

References

1) A.K. Geim and K.S. Novoselov, *Nat. Mater*. 6 (2007) 183.

2) J. B. Oostinga, H. B. Heersche, X. Liu, A. F. Morpurgo and L. M. K. Vandersypen, *Nat. Mater*. 7 (2007) 151.

3) H. Miyazaki, K. Tsukagoshi, A. Kanada, M. Otani and S. Okada. *Nano Lett*. 10(2010)3888.

4) Y. Zhang, T. T. Tang, C. Girit, Z. Hao, M. C. Martin, A. Zettl, M. F. Crommie, Y. R. Shen and F. Wang, *Nature*. 459 (2009) 820.

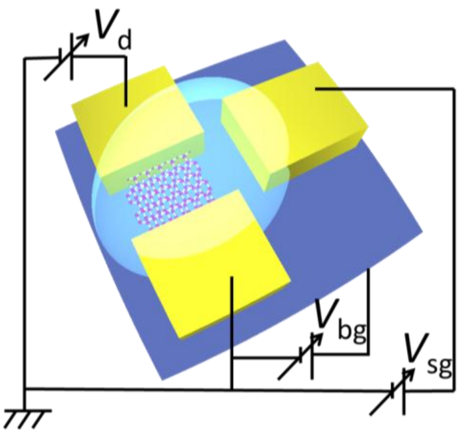

Fig. 1. Schematic diagram of our experimental setup.

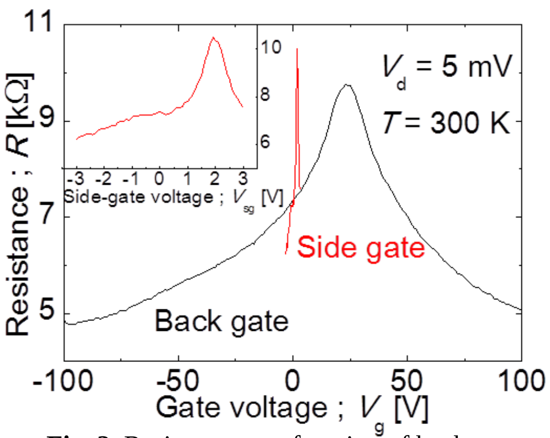

Fig. 2. Resistance as a function of back-gate voltage and side-gate voltage.

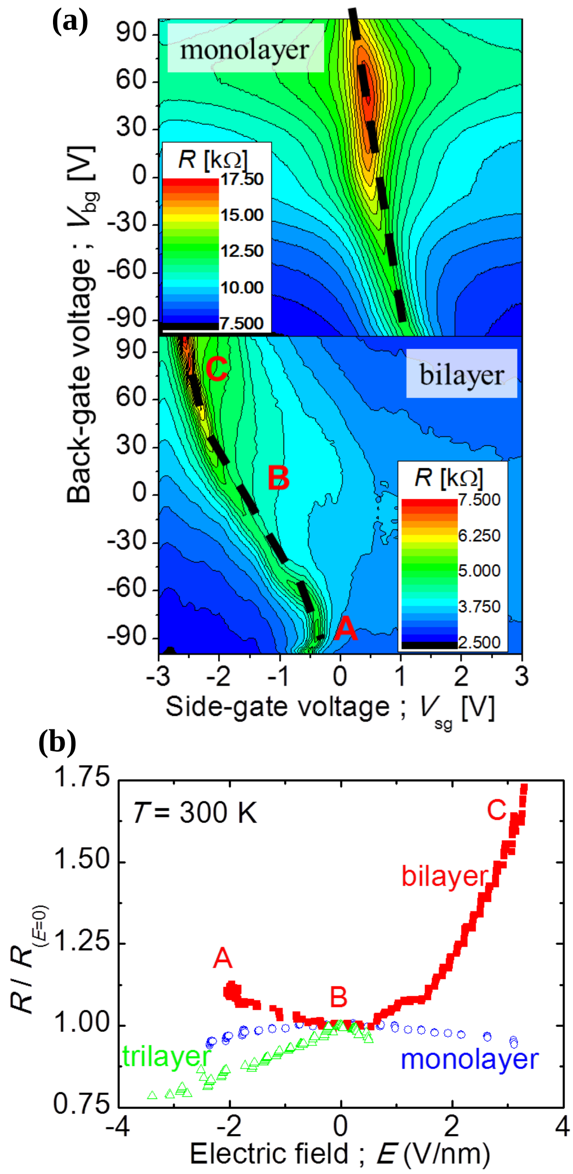

Fig. 3. (a) Contour plots of the resistance as a function of V_{bg} and V_{sg}. (b) Resistance at the neutrality point plotted against electric field. These curves are normalized to the resistance at the electric field of 0 V/nm.

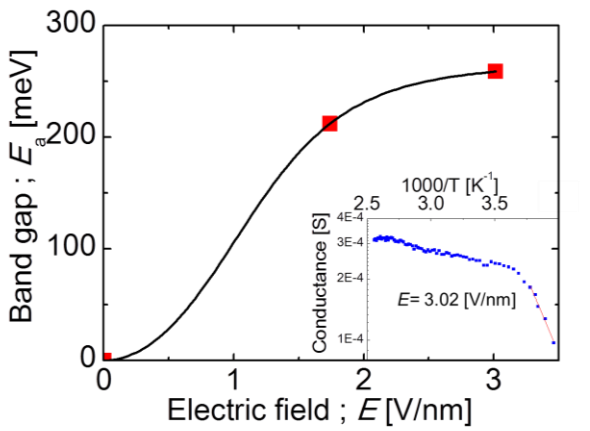

Fig. 4. Electric field dependence of band gap. Inset shows Arrhenius plot of conductance.