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Electric-field dependence of G-band spectra in bilayer graphene

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1. Introduction

Graphene is expected to find use as a building block in next-generation electronics such as field-effect transistors (FETs), high-frequency electronics, transparent electrodes, and high-sensitivity sensors [1] because of its mechanical strength, chemically stability, and extraordinary high mobility. However, graphene is a zero-gap semiconductor. When FETs with graphene channels are fabricated, the drain current is not switched off by adjusting the gate voltage. Thus, creating a band gap in graphene is necessary in order to realize graphene-based devices.

It is known that the band gap is formed with potential asymmetry between top and bottom layer in bilayer graphene due to applied electric field. In this study, we fabricated “dual gate structures” containing back gate (V_{bg}) and ionic-liquid side gate (V_{sg}) [2], and investigated effects of the carrier density and the asymmetry potential by Raman measurements.

2. Experimental

The graphene layers were extracted by a mechanical exfoliation and were put on Si substrates covered with a 300-nm-thick SiO_2 layer. An ionic liquid (DEME-TFSI) was placed into the bilayer graphene channel and onto the side-gate electrode patterned at a distance of approximately 20 μm from the channels without any passivation films (Fig. 1). The transfer characteristics in the ionic liquid revealed that the ionic-liquid-gated graphene FETs had extremely large transconductance, which is attributable to the formation of a thin electrical double layer in the ionic liquid with capacitance of 200-fold that of a SiO_2 layer [2]. The small optical absorption of ionic liquids in the visible range makes possible the Raman measurements.

3. Results and discussion

Figure 2 shows the resistance contour plots as a function of the back- and side-gate voltages of bilayer graphene. A ridge line indicating the charge neutrality was clearly observed. The charge densities in graphene were held constant on the ridge lines because of the balance between the back- and side-gate voltages. However, increases in resistance (red areas) were clearly observed both on the left and right side in the ridge line. The increases in the resistance are caused by generating a band gap in bilayer graphene due to applied electric field.

A G-band peak of bilayer graphene shows good fit almost with a single Lorentz function when Fermi level is located at the Dirac point (Fig. 3(a)). On the other hand, two peaks (G- and G+) were clearly observed when we applied ΔV_{sg} = -2.9 V (Fig. 3(b)), where ΔV_{sg} is a difference voltage between the side gate and charge neutrality voltage. The results suggest that the splitting of the G peaks is due to the change of the Fermi level at bilayer graphene.

Figure 4(a) shows the relative intensities of G- and G+ at the V_{bg} of 0 V as a function of ΔV_{sg}. At the V_{bg} and ΔV_{sg} of 0 V, the electric field corresponds to zero. G+ has smaller intensity than G- at the ΔV_{sg} of 0 V, on the other hand, the intensity of G+ became larger than that of G- at the lower side-gate voltage. The results reveal that inversion of G- and G+ intensities occurred at around ΔV_{sg} = -1.3 V.

Figure 4(b) shows ΔV_{sg} dependence of the intensities of G- and G+ at the V_{bg} of 60 V, revealed that the inversion of G- and G+ intensities was also observed. However, a ratio of intensities of G- and G+ at the lower side-gate voltage (ΔV_{sg} < -1.3 V) became larger and the transition of inversion became sharper (ΔV_{sg} ~ -1.3 V), which were considered to be due to the larger potential difference between top and bottom of graphene. Similar behaviors have been predicted in the theoretical study [3]. The results are due to the potential asymmetry between the top and bottom graphene layers with the electric field.

Furthermore, effects of the potential asymmetry were also observed in Raman shift. Figures 5(a) and 5(b) show ΔV_{sg} dependence of the Raman shift at the V_{bg} of 0 and 60 V, respectively. At the Dirac point, Raman shift of G+ at the V_{bg} of 60 V was positively shifted as compared with that of G+ at the V_{bg} of 0 V, resulting from the band gap generation of bilayer graphene.

3. Conclusions

In this study, we used a transparent liquid gate and made it possible to measure Raman spectra of bilayer graphene under electric field. Two G-band peaks were clearly observed, and their intensities and Raman shifts depend on the electric field. The results can be explained by the potential asymmetry between the top and bottom graphene layers with the electric field, resulting in formation of the band gap in bilayer graphene.

References
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[3] T. Ando and M. Koshino, J. Phys. Soc. Jpn. **78** (2009) 034709.

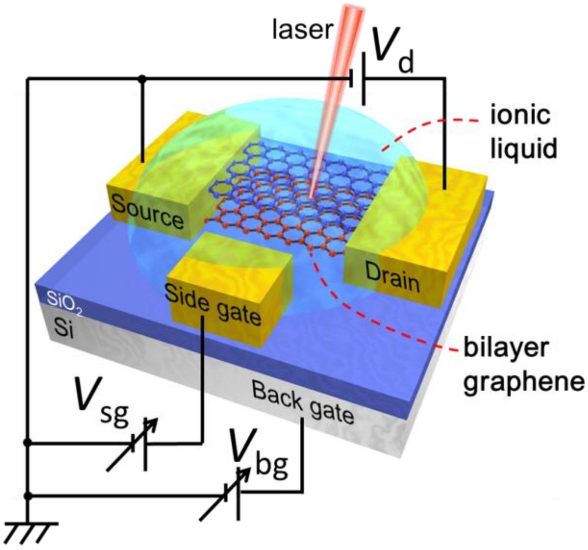

Fig. 1. Schematic diagram of the experimental setup.

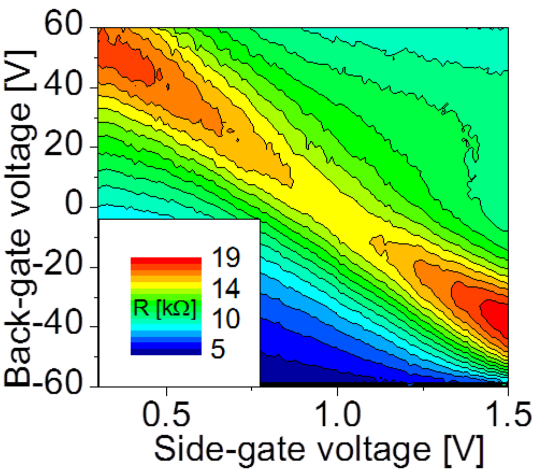

Fig. 2. Contour plots of the resistance as a function of V_{bg} and V_{sg}.

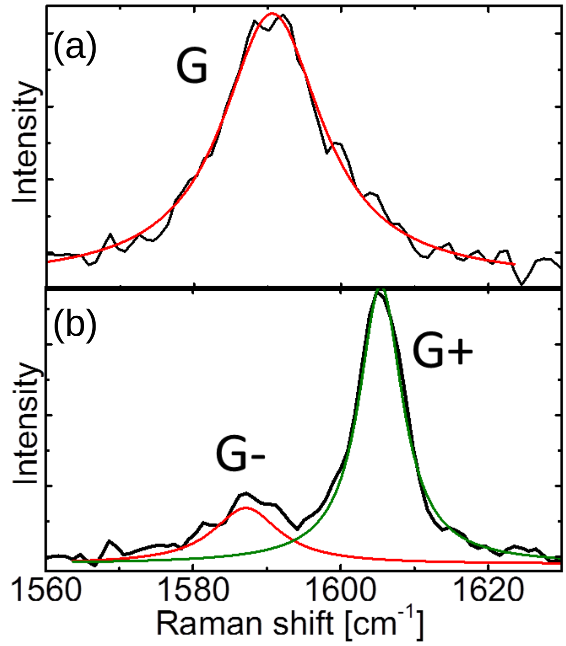

Fig. 3. Raman spectra of bilayer graphene at ΔV_{sg} of (a) 0 V and (b) -2.9 V.

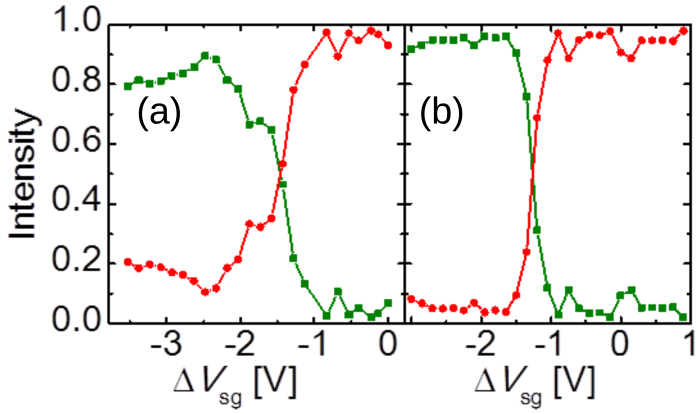

Fig. 4. Side gate dependences of intensities of G- and G+. at the back gate voltage of (a) 0 V and (b) 60 V.
Green and red plots correspond to G+ and G-, respectively.
Sum of G- and G+ in normalized to be 1.0.

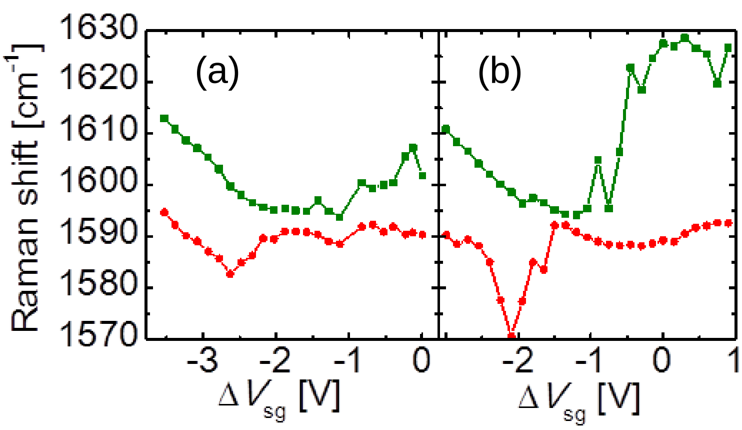

Fig. 5. Side gate dependence of Raman shift of G- and G+. at the back gate voltage of (a) 0 V and (b) 60 V.
Green and red plots correspond to G+ and G- energies, respectively.