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Formation of Quantum Dots in Graphene with Constrictions

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1. Introduction

Graphene is formed by single layer of carbon atoms, and has rapidly attracted growing attention from both experiment and theory. Some unusual properties such as only one-atom thickness and massless carrier make graphene one of the most interesting candidates for studying material physics. Moreover, as their extraordinary high mobility, graphene is expected to become new material for the building blocks of logic circuits. For development of these practical devices using graphene, it is necessary to investigate electrical characteristics of graphene nano-ribbons and quantum dots (QDs). In graphene nano-ribbons, recent researches showed the formation of band gap with decreasing nano-ribbon width [1, 2]. In this work, we have fabricated graphene QDs with two narrow constrictions, which were entirely carved from graphene, as shown in Fig. 1. The narrow constrictions are expected to act as tunnel barriers. Therefore, the carriers in graphene QDs will be confined by two narrow constrictions. In this study, the electrical characteristics in graphene QDs were investigated.

2. Experimental

The graphene layers were extracted from natural graphite by mechanical exfoliation onto highly n-doped Si substrates covered with a 90-nm-thick SiO_2 layer. The graphene is contacted by electro-beam (EB) lithography patterned Ti/Pd electrode. We defined EB-resist (ZEP-520A) mask by an EB lithography technique to protect chosen areas during oxygen reactive ion etching. As a result, we obtained desired graphene-QD structures. Figure 2 shows atomic force microscope (AFM) image of the fabricated graphene-QD structure. The device consists of single graphene QD with two narrow graphene constrictions, which were connected to source and drain electrodes. The *n*-doped Si wafer was used as a back gate. Figure 3 shows scanning electron microscope (SEM) image of the device. The image reveals that the dot diameter was estimated to be approximately 100 nm and the narrow graphene constrictions had several ten nm in width. In this study, the width of narrow graphene constrictions (W) dependence of the electrical characteristics was investigated at 8 K.

3. Results and discussion

The drain current (I_d) was plotted against the back gate voltage (V_g) of a graphene field-effect transistor before formation of QD structure at 300 K and 8 K in Fig. 4. The inset shows on the optical micrograph of the device. Ambipoler characteristics which is caused by band structure of graphene were observed at 300 K. This is consistent with other reports. At 8 K, only slightly decreased I_d was observed.

On the contrary, the drain currents were clearly oscillated against V_g at 8 K after the formation of graphene-QD structures. Figure 5 shows the I_d-V_g characteristics of the devices with different width (W) of 30, 35 and 45 nm at 8 K. With narrowing W, the broadening of gap in I_d-V_g characteristics and clearer Coulomb oscillations were observed. These strongly W dependent I_d-V_g characteristics indicate that the band gap in the two narrow constrictions became large, resulting in strong carrier confinement with narrowing W. Therefore, the narrow constrictions act as tunnel barriers. The inset of the Fig. 5 shows I_d contour plots as a function of the V_g and source-drain voltage of the device with 30-nm graphene constrictions. Clear Coulomb diamonds were observed. These results indicate that narrower constrictions and QD structures lead clear Coulomb oscillations. Finally, we fabricated a smaller graphene QD of 50 nm in diameter with two narrow constrictions of 10 nm. I_d-V_g characteristic of the device at 8 K is shown in Fig. 6. Clearer Coulomb oscillations were obtained. Moreover, its I_d showed good pinch-off characteristics at Coulomb blockade regions, indicating the formation of small QD structure in graphene.

4. Conclusions

We fabricated QDs in graphene with constrictions. At low temperature, Coulomb oscillations and Coulomb diamonds were clearly observed. Clear Coulomb oscillations observed in the device with smaller constrictions, indicating that they work as tunnel barriers. These graphene QD with narrow constrictions have high potentials for the practical applications of conventional logic circuits.

References

[1] Melinda Y.Han et al. Phys. Rev. Lett. 98, 206805 (2007)
[2] Xinran Wang et al. Phys. Rev. Lett. 100, 206803 (2008)

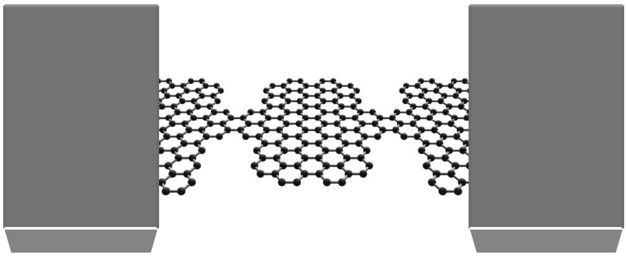

Fig. 1. Schematic structure of a QD in graphene with two narrow constrictions.

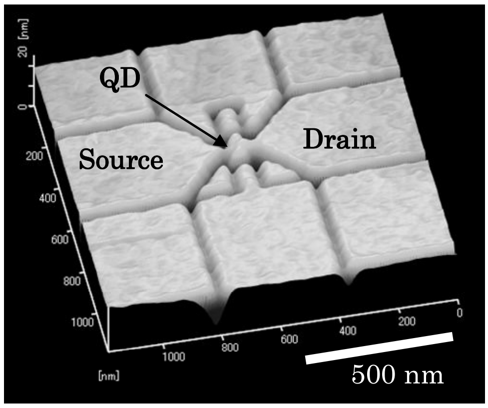

Fig. 2. AFM image of the device.

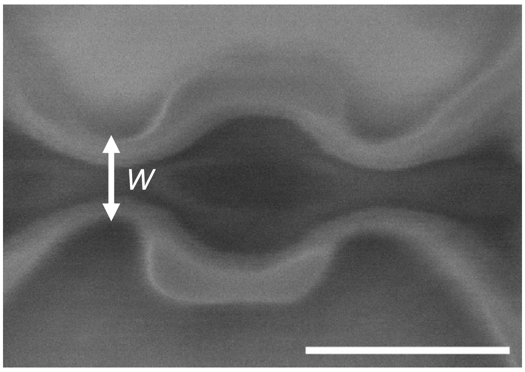

Fig. 3. SEM image of the device. The arrow shows width of constrictions. The scale bar is 100 nm.

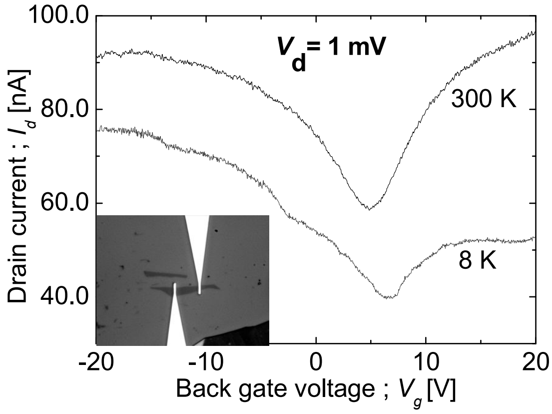

Fig. 4. I_d-V_g characteristics of the graphene at 300 K and 8 K. The inset shows the optical image of the device.

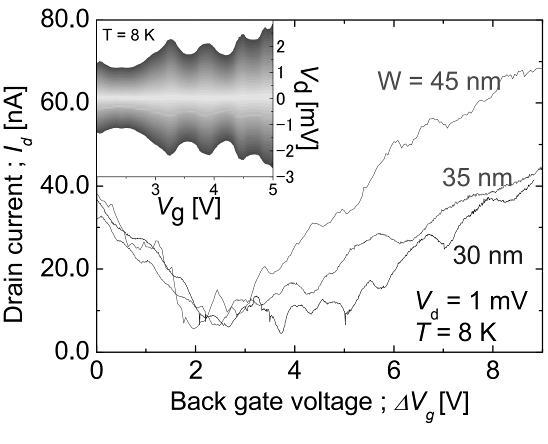

Fig. 5. I_d-V_g characteristics of the graphene QDs at 8 K. The inset shows the contour plots of $|I_d|$ as a function of V_d and V_g measured at 8 K.

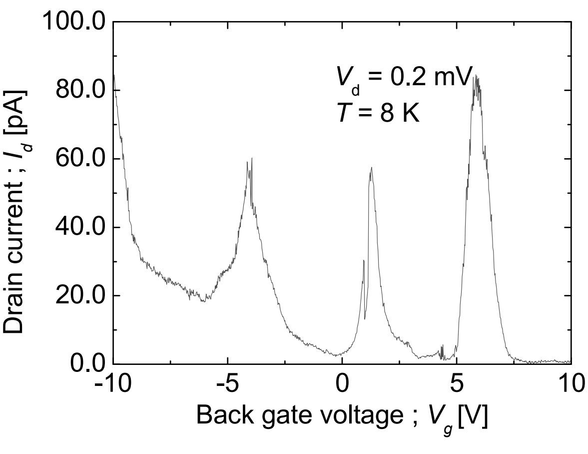

Fig. 6. I_d-V_g plot of the graphene QD with two narrow constrictions, which has 50 nm in diameter of the QD and 10 nm in width of constrictions.