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Low temperature electrical transport properties of suspended graphene nanoribbons grown by plasma CVD

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Abstract

Graphene nanoribbons (GNRs) which are edged stripes of graphene have high potential to be new alternative semiconductor materials with extraordinary properties, which can break through problems facing silicon electronics today. Nevertheless, GNR electrical properties have been hampered by a significant challenge. How to attain narrow GNR without defect and disorder becomes one of the crutial issues to develop GNR-based high performance optoelectrical devices. Here, we report electrical properties of suspended and narrow (~20 nm) GNR grown by a novel and scalable method using advanced plasma technology. It has been revealed that GNRs grown by our method behave as a single quantum dot without including significant defects. Based on that fact, it can be supposed that our newly invented method has high potential to lead GNR studies to realization of brilliant applications of GNR for various optoelectrical devices.

1. Introduction

Graphene nanoribbons (GNRs) have both the unique electronic and spin properties of graphene and a transport gap that arises from quantum confinement and edge effects. This makes them an attractive candidate material for the optoelectronic devices. However, GNRs study is facing significant challenges which make it difficult to use GNR as industrial application. One of these obstacles is how to get narrow GNR without defect and disorder. Furthermore when it comes to industrial application, it is necessary to integrate GNR devices. Up to now, ideal method which can give us narrow, defect-less and scalable GNR devices have not been developed. As a solution for that, we developed a novel method based on the advanced plasma CVD method [1,2] with nanoscale Ni catalyst (Ni nanobar) for directly fabricating suspended GNRs devices [3]. This method can make it possible to realize wafer scale synthesis of 1,000,000 suspended GNRs [4]. However, it has not been clarified yet about the detailed electrical transport properties of our suspended GNR, especially under the low temperature conditions. It is very important to fully understand the basic features of our suspended-GNR devices for future industrial applications.

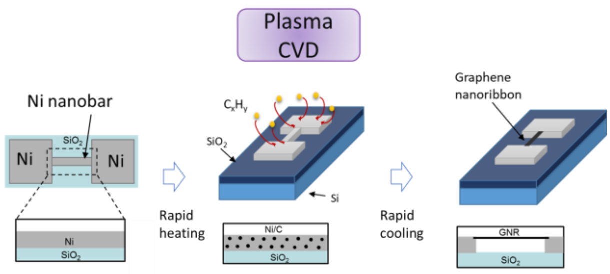

Fig. 1 Illustration of plasma CVD process for growth of GNR from Ni nanobar.

2. Results and discussion

2-1. Fabrication of suspended GNR devices

Suspended GNRs are able to be grown by simple plasma CVD process which is shown in Fig. 1. According to reported growth model [4], Ni nanobar contains significant amount of carbon during heating process with plasma irradiation. On the other hand, when it starts to cool, the GNRs could be nucleated on the surface of the liquid Ni nanobar. In this case, a large number of carbon atoms were used to form GNRs. At this time, carbon concentration in liquid Ni nanobar decreases. Since the low carbon concentration of liquid Ni nanobar is unstable, the nanobar is broken into two pieces. The droplets

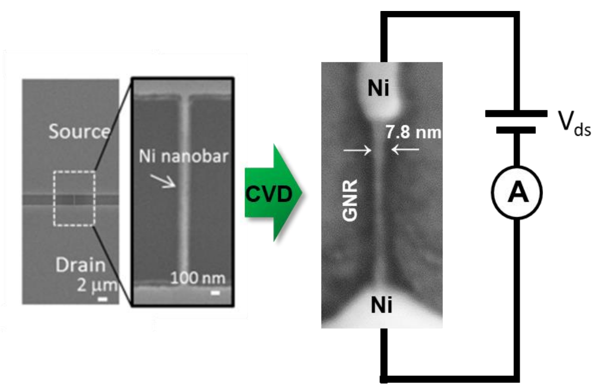

Fig. 2 Typical scanning electron microscope image of Ni nanobar before CVD (left) and GNR after CVD (right).

of Ni liquid move to electrode direction due to the capillary force, resulting in the formation of suspended GNR structures [4].

2-2.Low temperature electrical transport properties of suspended GNR

Electrical transport properties of suspended GNRs are carefully measured under the low (～15 K) temperature condition. Here, we are focusing GNRs devices which show Coulomb oscillation. It is possible to get very important information from Coulomb oscillation peak and Coulomb diamonds. With regards to observed Coulomb oscillations, surprisingly they are almost perfectly periodic and reproducible (Fig 3). Based on this coulomb peak spacing, gate capacitance can be calculated by eq. (1)

$$\Delta V_{peak} = e/C_g \tag{1}$$

where, ΔV_{peak} is peak spacing, e is elementary charge, and C_g is gate capacitance. Calculated gate capacitance is used for estimation of charge island size from plate capacitor model. However, we need to be careful that the charge island size value by plate capacitor model is only true for 2 dimensional model. In case of 1 dimensional structure such as GNRs, true value is not able to be calculated due to electric field concentration. To get to know charge island size in GNRs, we used reported equation considering electric field concentration [5].

$$C_g(w)/C_{g,2d}(w) \approx d/w \tag{2}$$

where, C_g (w) is calculated value with measured Coulomb peak spacing, $C_{g,2D}$ (w) is calculated gate capacitance by plate capacitor model, d is thickness of SiO_2 and w is the width of GNR. Eq. (1) and eq. (2) can allow us to caluculate the size of charge island. As a calculated result, it was found that estimated charge island area (1.0~1.5×10^3 nm^2) was in good agreement with the size of measured GNR (20 nm$\times$160 nm=3.2×10^3 nm^2). This indicates that whole GNR plays a role as single charge island. If GNR includes many defects, GNR should work as multi quantum dots. From this fact, we can propose that there is less defect in our suspended GNR. The reason why we could attain less defect can be due to our unique bottom up process and suspended structure. In detail, our process does not have post process for device fabrication, which can avoid from inducing defect and disorder. The suspended structure can also contribute to suppressing the impurity scattering arising from the contract between SiO_2 substrate and GNR. Based on these results, it can be conjectured that the suspended GNR grown by our novel plasma CVD method possess outstanding advantages such as narrow width, defect less, and scalable GNR devices fabrication which should be very useful for the realization of future high performance GNR-based optoelectrical devices.

3. Conclusions

The low temperature electrical measurement reveals that suspended GNR grown by our novel plasma CVD method shows periodic oscillation and obvious Coulomb diamonds features. By analyzing Coulombs oscillation behavior, it is found that the charge island size is almost same with the size of GNR, indicating whole GNR works as a single charging island. This indicates that our GNRs have less defect, which should be because our device can be made with as-grown suspended GNRs. These results are useful for the next generation high-performance optoelectronic device application [6-8].

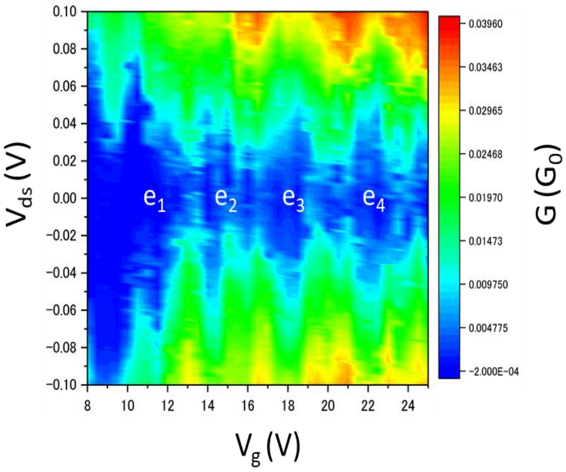

Fig. 3 Overview of 2D color map of conductance (G) normalized by e^2/h (G_0) against drain-source bias (V_{ds}) and gate bias (V_g) voltage.

Acknowledgements

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