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Fabrication of graphene nanoribbon transistors with high on/off ratio using advanced plasma CVD

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Abstract

Graphene nanoribbons (GNR) combine the unique electronic and spin properties of graphene with a transport gap that arises from quantum confinement and edge effects. Up to now, we have developed a novel method based on the advanced plasma CVD with nanoscale Ni catalyst (Ni nanobar) for directly fabricating suspended GNR devices. However, there remain spaces to be studied about this method, especially for structural flexibility and on/off current ratio. In this study, we found that sub 10 nm width GNR can easily be synthesized from Ge nanobar. The on/off ratio of GNR grown from Ge nanobar shows very high on/off ratio (~10^4) at room temperature. This result shows that GNR grown from Ge nanobar includes higher potential for the future application of GNR for various semiconductor devices.

1. Introduction

In recent years, graphene nanoribbon (GNR), strips of two-dimensional (2D) graphene into one-dimensional (1D) structure gather intense attentions because of their superior electrical features. Although GNR can be made in a variety of ways, the reliable site and alignment control of GNR with high on/off current ratios remains a challenge.

Until now, we have developed a novel method based on the advanced plasma CVD [1-5] with nanoscale Ni catalyst (Ni nanobar) for directly fabricating suspended GNR devices (Fig. 1(a)) [6, 7]. Although this method has outstanding advantages in terms of precise site and alignment controlled growth of suspended GNR, there remain spaces to be studied about this method, especially for on/off current ratio. At the current state, GNR grown by Ni nanobar has relatively low on/off (~5). GNR devices with much higher on/off ratio are necessary for the use of GNR in various semiconductor applications.

2. Results and discussion

2.1 Fabrication of GNR transistors

Suspended GNRs are able to be grown by simple plasma CVD process. According to reported growth model [7], 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 of Ni liquid move to electrode direction due to the capillary force, resulting in the formation of suspended GNR structures (Fig. 1(a)) [7].

2.2 Improving on/off current ratio of GNR transistor

We attempted to improve on/off current ratio of field-effect transistor with GNR grown by advanced plasma CVD. It is known that the band gap of GNR is inversely proportional to the width of GNR, indicating narrower GNR can obtain higher on/off. To narrow down the width of GNR, GNR growth was carried out with various kinds of metal nanobars such as Ni, Cu, and Ge as catalysts. It was found that GNR can be grown from various nanobar catalysts (Fig. 1(b-d)). Then, careful analysis of GNR width was carried out for those GNR grown from various nanobars. It is found

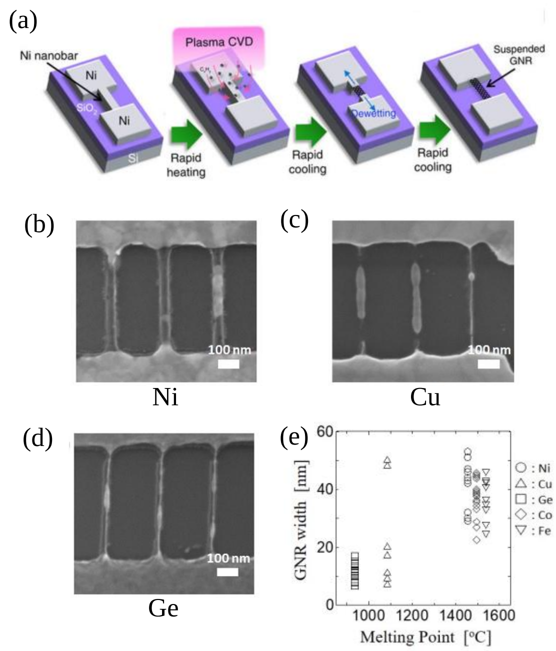

Fig.1 (a) Schematic illustration of GNR growth with plasma CVD from nanobar catalyst. (b-d) Typical scanning electron microscope (SEM) images of GNR synthesized from various nanobar catalysts. (b), (c), (d) corresponds with Ni, Cu, and Ge nanobar catalysts, respectively. (e) Plot of GNR width as a function of melting point of nanobar catalysts.

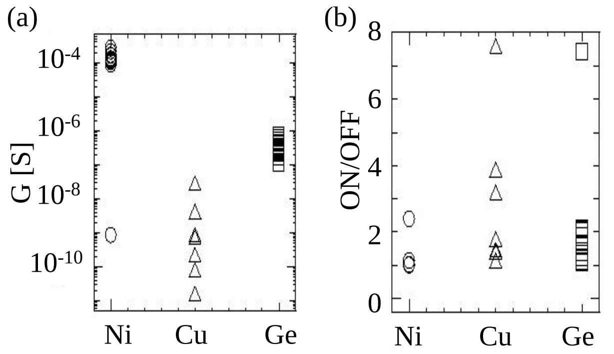

Fig.2 Plots of (a) conductance and (b) on/off ratio of GNRs synthesized from various nanobar catalysts.

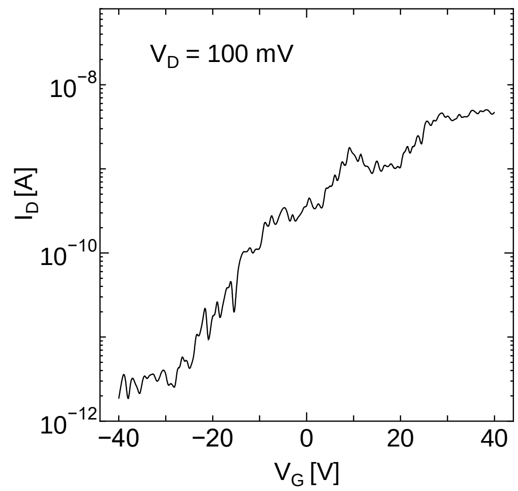

Fig. 3 Typical drain-source current (I_D) - gate bias voltage (V_G) curves of GNR devices fabricated with Ge nanobars under the adjusted plasma conditions.

that there is a clear correlation between GNR width and melting point (MP) of bulk metals used for nanobars. The nanobars with relatively low MP such as Cu and Ge can grow narrower (below 10 nm) GNR than that of higher MP materials such as Ni (Fig. 1(e)). Based on our previous study about the growth model of GNR, it is found that the nanobar structure becomes liquid phase during plasma CVD [7]. Although the initial width of nanobars was same for all kinds of nanobars, Cu and Ge nanobars may shrink before GNR nucleation due to the relatively low MP, resulting in the growth of narrower width of GNR.

The electrical measurement was also carried out for the GNR grown from various kinds of nanobars. Conductance (G) of GNR grown from Ni nanobar shows very high value, whereas GNR grown from Cu nanobar is the smallest within three kinds of nanobars. Relatively high on/off ratio can be observed from GNR grown from Cu and Ge nanobar. These can be explained that GNR grown from Cu and Ge nanobar may possess thinner layer than that of GNR grown from Ni nanobar. Since relatively high conductance and high on/off ratio can be obtained with Ge nanobar, further adjustment of growth conditions were carried out with Ge nanobar. Based on the previous study with Ni nanobar, supply of carbon flux is known as a key factor to decide the structure of GNR. Then, we adjust the carbon flux by changing the plasma parameters during CVD process. Surprisingly, the on/off ratio of GNR grown from Ge nanobar under the best growth condition shows very high on/off ($\sim10^4$) at room temperature (Fig. 3). Since our unique plasma process possesses significant advantage for the integrated synthesis of GNR, this high on/off ratio GNR grown from Ge nanobar can contribute to realizing high-performance logic circuit with integrated GNRs.

3. Conclusions

GNR growth from various kinds of nanobar catalysts is realized with advanced plasma CVD. It is found that GNR can be grown from many kinds of nanobar catalysts such as Ni, Cu, and Ge. GNRs grown from Ge nanobar shows relatively high current conductance and high on/off ratio compared with that of GNR grown from other kinds of nanoars. Through the adjustment of plasma conditions during the CVD synthesis of GNRs, on/off ratio of GNR device can be increased up to $\sim10^4$ at room temperature. Since our study enable to grow high on/off GNR with accurate position selectivity, this result can contribute to realizing high-performance GNR-based optoelectrical device [8-10].

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