Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp595-596

Nanoscale Fabrication of Planar-type Structures on thin Graphite Flake using Focused Ion Beam System

Gunasekaran Venugopal[1] and Sang-Jae Kim[2]

[1]Graduate School of Science and Technology, Department of Mechanical, Energy and System Engineering
Jeju National University, Jeju 690-756, Korea
[2]Research Institute for Advanced Technology, Jeju National University, Jeju 690-756, Korea
Phone: +82-64-754-3715 Fax: +82-64-756-3886 E-mail: kimsangj@jejunu.ac.kr

1. Introduction

In this paper, we present a unique method for nanoscale fabrication of planar-type structures/patterns along (*ab*-plane and *c*-axis) on thin graphite layer by using a three-dimensional focused ion beam (FIB) etching technique. We have fabricated several in-plane areas of planar-type nanostructures/patterns on thin graphite layer (thickness ~ 500 nm) using FIB. Those in-plane area sizes were 6 μm x 6 μm, 6 μm x 4 μm and 6 μm x 2 μm. The *c*-axis stack with the height of several nanometers was also fabricated. The electrical transport characteristics were studied for these fabricated structures. We have observed nonlinear (curve-like) transport behavior from the current *(I)* - voltage *(V)* characteristics which have shown a clear transition from an ohmic behavior at 300 K to curve-like nonlinear characteristics below 110 K for *ab*-plane and *c*-axis stack. A clear nonlinear characteristics has been observed at 25 K. The resistance *(R)* - temperature *(T)* and *I-V* characteristics curve of the *ab*-plane and *c*-axis stack strongly resemble this transition behavior. These results show the superiority of graphite-nanostructures for futuristic nonlinear electronic device applications.

2. Background

Novel carbon-based structures represent key materials for new technological applications and devices. Graphite is a three dimensional (3-D) material which has a sheet-like layered structure where the carbon atoms all lie in a plane and are only weakly bonded to the adjacent graphite sheets [1]. It is normally a basic material for all above carbon allotropes. Recently, the research on graphite materials such as two-dimensional graphene (single atomic layer of carbon), zero dimensional fullerenes (C_{60}) and carbon nanotubes have attracted much attention by their unique properties for micro and nano-electronic applications. Particularly, graphene becomes an active replacement material for silicon which is being used heavily in semiconductor industries nowadays [2]. Each sheet has hexagonal lattice of carbon bonded by strong σ bonding (sp^2) in the *ab*-plane. The perpendicular π-orbital electrons along the *c*-axis are responsible for *ab*-plane conductivity [3]. In this paper, we report a detailed fabrication technique for planar-type nano-structures on thin graphite layer and their nonlinear characteristics observed below 110 K for *ab*-plane and *c*-axis stack fabricated by using focused ion beam. In general, the electronic devices such as diodes, bipolar junction transistors (BJT's), and field effect transistors (FET's) are described in terms of their nonlinear *I-V* curves.

Recently, these devices have been developed with respect to low noise, low power, and high electron mobility transistor applications [4]. Their electronic transport properties present remarkable scientific and technological potential. The studies on bulk graphite have been investigated for many years, however there has been no work reported on the fabrication of planar-type nanostructures on thin graphite layer using focused ion beam. As well as the observation of nonlinear characteristics have not been ever reported elsewhere. Thus, our research has focused primarily on the fabrication of nano-structures and their nonlinear *I-V* characteristic studies.

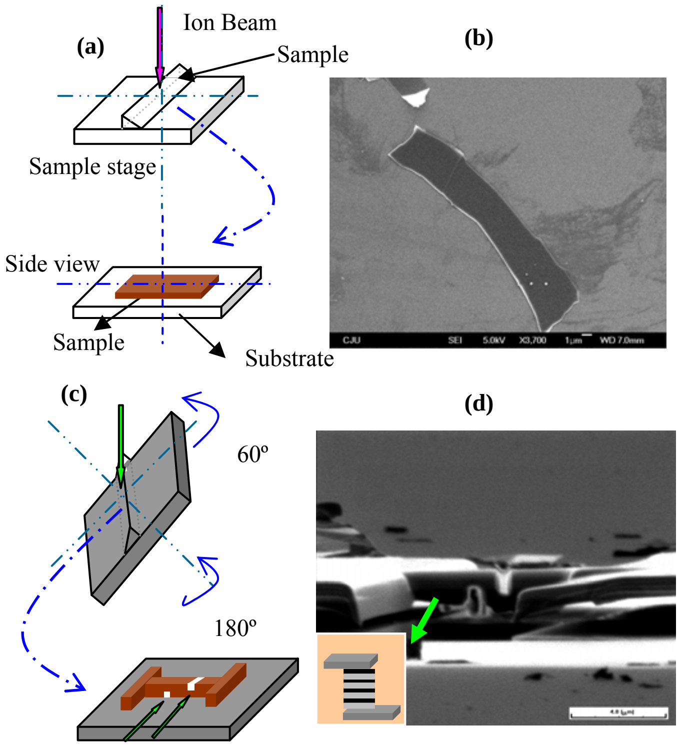


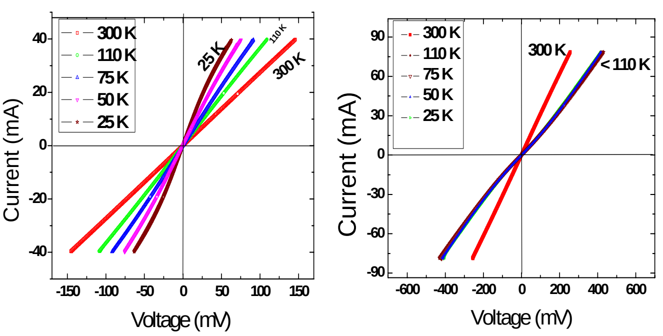
Fig. 1 FIB nanofabrication process is shown. (a) Schematic drawing for *ab*-plane milling process (b) SEM image of a thin graphite flake on Si/SiO2 substrate exfoliated from bulk graphite. (c) Schematic drawing for *c*-axis stack fabrication process (b) a FIB image of a fabricated *c*-axis stack on a graphite flake. (Inset shows the stack arrangement along *c*-axis).

3. Fabrication of Nanoscale Planar-type Structures

In this study, we used thin graphite crystallites extracted from highly ordered pyrolytic graphite (HOPG) using the mechanical exfoliation technique, as this method had been shown to form perfect crystallites [5]. Fig. 1 shows the detailed nanofabrication process of planar-type structures along (*ab*-plane and *c*-axis) using focused ion beam (FIB) 3-D etching technique. Those in-plane area sizes were 6 µm x 6 µm, 6 µm x 4 µm and 6 µm x 2 µm. These in-plane areas were etched by the tilting the sample stage by 30º anticlockwise with respect to ion beam and milling along *ab*-plane [ref. Fig.1(a)]. The *c*-axis stack with height of several nanometers was fabricated [Fig.1(c)] by rotating the sample stage by an angle of 180º and then tilted by 60º anticlockwise with respect to ion beam and milled along the *c*-axis. The fabricated *c*-axis stack size was W = 2 µm, L= 1 µm, H = 200 nm which is shown in Fig. 1(d). The schematic picture of stack arrangement in graphite layer is shown as inset in Fig. 1(d). These nano-fabrication etching details were reported in detail by S.J. Kim *et al* [6].

4. Results and Discussion

The electrical transport characteristics were performed for both *ab*-plane and *c*-axis stack structures using four-probe contact measurement by using closed-cycle refrigerator system. In Fig. 2(a), we show the *I-V* characteristics of the 6 µm x 2 µm size planar-type structure. The fabricated in-plane structures were shown a linear ohmic behavior at 300 K which turns into nonlinear behavior below 110 K. A clear nonlinear characteristic has been observed at 25 K. We propose that below 110 K there is a rapid decrease in effective charge carriers which can stimulate the ohmic behavior into nonlinear characteristics. Most noticeably, a symmetricity in the *I-V* curves has been observed. We also observed similar characteristics as well for all other fabricated planar-type structures of sizes 6 µm x 6 µm and 6 µm x 4 µm. Similar to the in-plane planar-structures, the *c*-axis stack structures were also exhibited linear-ohmic behavior at 300 K and the same has been turned into nonlinear characteristics at 25 K.



(a) (b)

Fig. 2 The *I-V* characteristics of 6 µm x 2 µm size planar-type structure [Fig. 2(a)] and *c*-axis stack [Fig. 2(b)] show linear-ohmic behavior at 300 K and the same is turned into nonlinear curve-like characteristics below 110 K.

In Fig.2(b), the *I-V* characteristics of *c*-axis stack is shown. Below 110 K, there is no large shift in *R* value between the temperatures 110 K, 75 K, 50 K and 25 K. Hence these temperatures exhibit nonlinear characteristics all together with very low difference in *R* value. But *I-V* characteristics of *c*-axis stack exhibits a non-symmetric transition from linear to nonlinear behavior.

From resistance *(R)* – temperature *(T)* characteristics measurement for *c*-axis stack, we observed semiconducting behavior till 50 K and then metallic behavior below 50 K. This is well agreed with previous theory reported by K. Matsubara *et al* [7]. Similarly the fabricated in-plane structures exhibit a typical metallic behavior similar to the characteristics observed for bare graphite flake. As the *ab*-plane and *c*-axis stack show their respective metallic and semiconducting transport characteristics, the transition from linear to nonlinear behavior in their *I-V* curves clearly indicates their respective behavioral directionality. Also the *ab*-plane and *c*-axis stack transport results were compared from which we declare that the *c*-axis stacks behave as a high barrier to charge carrier tunneling. This is because of the high resistance generated by weakly bonded adjacent layers in the stack [1].

5. Conclusions

In summary, we have successfully fabricated nanoscale planar-type structures of graphite layer and their transport characteristics were discussed. The nonlinear characteristics of graphite flakes (along *ab*-plane and *c*-axis) has been described using the concept of effective charge carriers transport phenomenon. Our fabrication technique and observation of linear-to-nonlinear transport behavior of this nanostructures/pattern might be helpful for further graphite-based nonlinear electronic device applications.

Acknowledgements

We gratefully thank Prof. H.– J. Lee, POSTEC, Korea for supplying graphite material for our research and his valuable suggestions.

References

[1] B. T. Kelly, Applied Science:London, Englewood, N.J., (1981) 267.

[2] S. J. Wind, J. Appenzeller, R. Martel, V. Derycke, and Ph. Avouris, Appl.Phys. Lett., **80** (2002) 3817.

[3] S. Banerjee, M. Sardar, N. Gayathri, A.K. Tyagi, and Baldev Raj, Appl.Phys. Lett., **88** (2006) 0621116.

[4] R. Quay, K. Hess, R. Reuter, M. Schlechtweg, T. Grave, V. Palankovski, and S. Selberherr, IEEE Trans. Electron Deices, **48** (2001) 210.

[5] K. S. Novoselov, A. K. Geim, S.V. Morozov, D.Jiang, Y. Zhang, S.V. Dubonos, I. V. Grigorieva, and A. A. Firsov, Science, **306** (2004) 666.

[6] S. J. Kim, J. Chen, K. Nakajima, T. Yamashita, S. Takahashi and T. Hatano, J. Appl. Phys. **91** (2002) 8495.

[7] K. Matsubara, K. Sugihara and T. Tsuzuku, Phys. Rev. B **41** (1990) 969.