Nano-scale Junction Fabrication on Thin Graphite Flakes using Focused Ion Beam

*구나세카란 [1], #김상재 [2]
*Gunasekaran Venugopal (guna@jejunu.ac.kr)[1], #Sang Jae Kim[2]
[1] Nano Materials and System Lab, Graduate School of Science and Technology, Jeju National University, Jeju, Korea
[2]Faculty of Mechatronics Engineering and Research Institute of Advanced Technology, Jeju National University, Jeju, Korea

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1. Introduction

We present in this paper, a unique method for nanoscale fabrication of junctions along *c*-axis of thin graphite layer by using a three-dimensional focused ion beam (FIB) etching technique. Since graphite is considered as layered-structure material, the two layers with inter atomic distance of 0.34 nm can be considered as a nano-scale junction. We have fabricated stacked junctions with 100 nm height which could contain many junctions along *c*-axis. A thin graphite layer (thickness ~ 500 nm) was chosen for FIB fabrication. The electrical transport characteristics were studied for these fabricated nanoscale junctions from 25 K to 300 K. We have observed a nonlinear (curve-like) transport behavior from the current *(I)* - voltage *(V)* characteristics. The stack with in-plane area A of 0.5 μm^2 showed nonlinear concave-like *I-V* characteristics even at 300 K; however the stack with A of > 0.5 μm^2 were shown an ohmic-like *I-V* characteristic at 300 K for both low and high-current biasing. It turned into nonlinear characteristics when the temperature goes down. Since the fabricated stacked-junction contains multiple elementary junctions along the *c*-axis, the nonlinear concave-like *I-V* curves of the tunneling characteristics appear. These results show the superiority of graphite-nanostructures for futuristic nonlinear electronic device applications.

2. Background

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. In graphite, 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 [2]. 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. 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 nanoscale stacked-junction on thin graphite layer using focused ion beam. As well as the observation of nonlinear characteristics have not been ever reported elsewhere.

In this paper, we report a detailed technique for fabricating nanoscale-junctions along *c*-axis of thin graphite layer using focused ion beam 3-D etching technique and their electrical transport characteristics at various temperature range from 25 K to 300 K.

3. Fabrication of Nanoscale Stacked-Junctions

In this study, we used thin graphite flakes extracted from highly ordered pyrolytic graphite (HOPG) using the mechanical exfoliation technique, as this method had been shown to form perfect crystallites [3]. Fig. 1 shows the detailed nanoscale fabrication process of stacked junction along *c*-axis of thin graphite flake using focused ion beam (FIB) 3-D etching technique. Two samples with different in-plane area of sizes 0.5 µm × 0.5 µm and 2 µm × 1 µm were fabricated and analyzed their transport characteristics were presented here. 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(b)] 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 = 0.5 µm, L= 0.5 µm, H = 100 nm which is shown in Fig. 1(c). The schematic picture of stack arrangement in graphite layer with indication of current flow direction (yellow arrow) is shown as inset in Fig. 1(c). These nano-fabrication etching details were reported in detail by S.J. Kim *et al* [4].

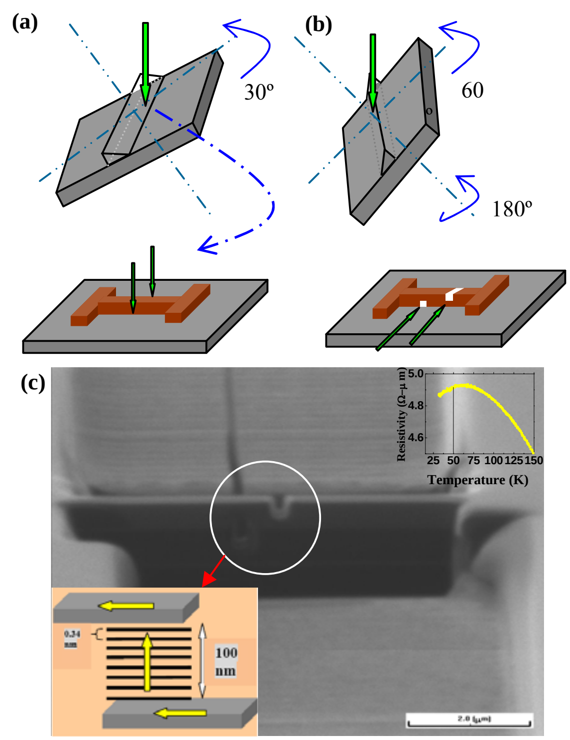

Fig. 1 (a-b) The schematic diagram of FIB fabrication process for *ab*-plane and *c*-axis etching. (c) The FIB image of *c*-axis stack fabricated on graphite layer. The stack size was W =0.5µm, L = 0.5µm, H = 100 nm. (image scale bar is 2 µm). Inset (left bottom) shows the schematic diagram of stack arrangement along the c-axis. The *ρ-T* characteristics of this sample is shown in top right inset.

4. Results and Discussion

The electrical transport characteristics were performed for the fabricated stacked-junction by using closed-cycle refrigerator (SUMITOMO CCR-4K, Japan) system. Four-probe contacts were made using silver paste and were annealed at 350 C to avoid contact resistance. In Fig. 2, we show the *I-V* characteristics of the nanoscale stacked-junction of W =0.5 µm, L = 0.5 µm, H = 100 nm. We observed a nonlinear concave-like *I-V* characteristics at all

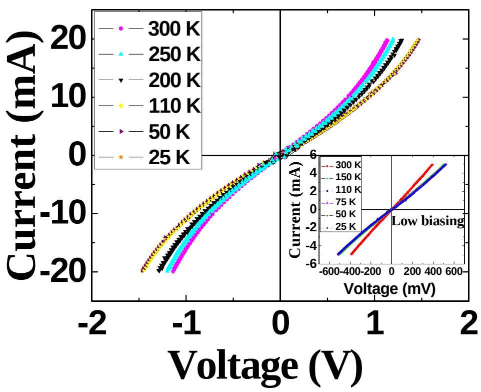

Fig. 2 The *I-V* characteristics of submicron stack with *A* of $0.5\mu m^2$ showing nonlinear concave-like characteristics. Inset (top centre) shows *ρ-T* characteristics of submicron-stacked junction.

studied temperatures (25 K, 50 K, 110 K, 200 K, 250 K and 300 K) for high biased current (20 *m*A). For low biased current, it shows linear-ohmic behavior at 300 K and down to 25 K as shown in inset (right bottom) of Fig. 2. At 25 K, the stack resistance was found as 75 Ω. The resistivity versus temperature (*ρ-T*) relation of the nano-scale junction is shown as inset (top-right) in Fig.1. We observed a semiconducting behavior till 50 K and then metallic behavior below 50 K. In the case of stack with *A* of 2 μm^2 (Fig. 3) we observed an ohmic behavior at 300 K for both low and high-current biasing. This leads to nonlinear concave-like characteristics when the temperature goes down. We noticed that there is a significant overlap of *I-V* curves for temperatures 110 K, 75 K, 50 K and 25 K. For low-biasing, linear *I-V* characteristics are observed at all studied temperatures from 300 K to 25 K. No nonlinear behavior is observed for the both cases when the sample is low-biased. We observed higher conductivity at 25 K and 50 K than the conductivity observed at 75 K.

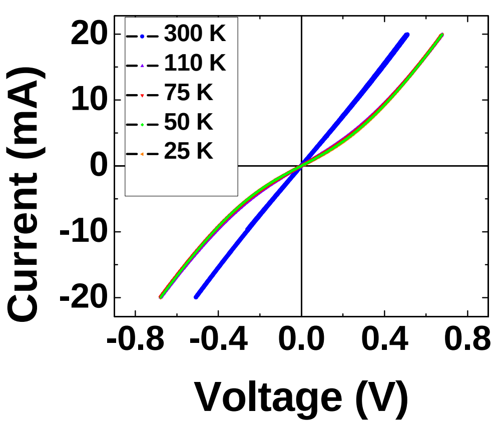

Fig. 3 The *I-V* characteristics of submicron stack with *A* of $1\mu m^2$ shows ohmic behavior at 300 K for both low and high biasing.

Our results of *c*-axis stack conduction well agree with earlier observation reported on *c*-axis conduction by Matsubara *et* al [5]. For graphite stacks bigger than 1 μm^2, we did not observe nonlinear *I-V* characteristics at 300 K even at high biasing. With a decrease of the stack size down to 0.5 μm^2, the junction shows clear nonlinear concave-like *I-V* characteristics for both 300 K and 25 K. Since the fabricated stack contains multiple elementary junctions along the *c*-axis, the nonlinear concave-like *I-V* curves of the tunneling characteristics appear. The appearance of nonlinear *I-V* characteristics may be partially due to the thermal activation or self heating effect [6], as the sample is biased with high-current which could destroy some parallel conductive paths [7].

We also explain this behavior in connection with the stack capacitance. Since the stack consists of multiple elementary junctions along the *c*-axis, each junction can be considered as a parallel-plate capacitor separated with the interlayer distance of 0.34 *n*m. Assuming the value of dielectric constant $\xi_r = 1$ (for air between the two layers) and $\xi_0 = 8.854\times10^{-12}$ *F/m*, we calculated the capacitance value of these stacks. We found that the capacitance of stack with *A* of 0.5 μm^2 is found as smaller than the capacitance value of stack with *A* of 1 μm^2. As it is well known, the tunneling current in a tunnel junction of small capacitance *C* can be blocked by the charging effect [8] and the charging effects become even stronger in the arrays of the small junctions [9]. Thus the whole stack with *N* junctions can effectively work as a single unit with the charge energy being *N* times higher than the charging energy of a single junction[10]. Due to this reason, the nonlinear characteristics were observed more clearly in the stack with *A* of 0.5 μm^2 even at 300 K since their capacitance value is very small.

5. Conclusion

In summary, we have successfully fabricated stacked junctions on thin graphite flake using FIB and their transport characteristics were discussed. The stack with *A* of 0.5 μm^2 showed a nonlinear concave-like *I-V* characteristic even at 300 K; however the stacks with *A* of > 0.5 μm^2 were shown an ohmic-like *I-V* characteristics at 300 K for both low and high-current biasing. The in-plane area dependence of stack capacitance was also discussed and the observation of nonlinear characteristics of submicron stacks were explained in connection with the stack capacitance.

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