Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp511-512

Staircase Conductance in Asymmetric Work Function Contacted Graphene-Nanoribbon Devices

Ahmed. M. M. Hammam[1,2], Manuharan Muruganathan[1] and Hiroshi Mizuta[1,3]

[1] JAIST
1-1 Asahidai, Nomi, Ishikawa 923-1292, Japan
Phone: +81-761-51-1573 E-mail:a-hammam@jaist.ac.jp
[2] Minia University. Main Road - Shalaby Land, Minia, 11432, Egypt
[3] Hitachi Cambridge Laboratory, Hitachi Europe Ltd., CB3 0HECambridge, United Kingdom

Abstract

In this work, we study the formation of graphene p-n junctions by using the metal-contact induced doping. Two different metal nickel and aluminum are used to form graphene p-n junction. We investigated the effect of the channel length (Lg) in the p-n junction formation. Devices with Lg > 500 nm show two Dirac points (DP) in the back-gate characteristics. However, shorter devices (Lg < 500 nm) the tow DPs cannot be resolved. This may be ascribed to the increase in the transfer length which inversely proportional to the low sheet resistance at short L_g. At low temperature (~ 15 K), conductance staircase behavior is observed in the devices of Lg < 500 nm. However, longer devices characterized by kinks. Scanning electron microscope (SEM) images confirmed the formation of cracks and narrow constrictions due to the high uniaxial stress from Al contacts, which is responsible for the ballistic conductance plateau in short junctions.

1. Introduction

Graphene p-n junction is the building block of a wide range of graphene-based nanoelectronics applications; such as Graphene photo-detection, photoemission, and graphene tunnel field-effect transistor. Electrostatic doping is the main technique to implement the required doping in all previous applications [1,2]. However, electrostatic doping increases the complication of device fabrication and limits the scaling possibility. Theoretical and experimental studies confirmed the graphene doping by metal contacts [3,4]. Charge transfer at the interface of graphene-metal results in doping of graphene sheet covered by metals. The work function (W_F) difference between graphene (W_F= 4.6 eV) and the metal determine the doping type. In general, there are two classes of the metal-graphene interface: 1) chemisorption and 2) physisorption interface. The electronic structure of graphene is strongly altered in chemisorption, but weakly affected in physisorption [3]. Here, we are using two metals with different work functions as a doping source. Based on the work function difference (ΔW_F) between graphene and metal contacts, doping level and type can be controlled [3]. Metals with lower W_F (e.g. aluminum) expected to introduce n-type doping [3]. In contrast, metals with larger W_F (e.g. nickel) introduce p-type doping [4]. In this work, aluminum (W_F =4.21 eV) and nickel (W_F =5.01 eV) is used as a metal contact for junction formation. Graphene nanoribbons (GNR) with different width(W)/length (L_g) ratios have been studied at room temperature and low temperature as well.

2. Experimental Methods

Here, a commercial chemical vapor deposition (CVD) grown single-layer graphene is transferred on top of a SiO_2 (285 nm)/Si substrate. To decrease the amount of PMMA residues after the transfer process that can degrade the carrier mobility, we put the sample in hot Acetone for 30 min, followed by annealing in forming gas for 3 hrs at 250 ºC. Electron beam lithography (EBL) followed by thermal evaporation and the lift-off technique are used to fabricate aluminum and nickel contacts. Symmetrically contacted devices (Al-Al and Ni-Ni), as well as asymmetrically contacted devices (Al-Ni), were fabricated. In this study, all devices have GNRs with 500 nm width but different lengths. In symmetrical and asymmetrical devices GNR length (L_g) ranging from 100 nm to 2000 nm. Narrow GNRs are achieved by EBL- reactive ion etching (RIE) technique. The sample was annealed at 250 ºC in a vacuum for 3 hrs before electrical measurements.

3. Results and Discussion

For Al-Ni long junctions of (W/L_g<1), (as shown in Fig. 1b) two conductance minima appear at back-gate characteristics of graphene junction. These two minima indicate the existence of two Fermi levels through the device and the formation of a p-n junction. The difference between the two minima (ΔV_{BG}) is proportional to the potential barrier between the p-type and n-type regions. This behavior can be attributed to the physisorption interaction at the graphene-Al interface. As the electronic structure of the graphene sheet covered by Al is weakly disturbed, Fermi-level can be modulated by the global back-gate. The device works as a p-n junction between the two DP (i.e. the junction is bipolar). As the back-gate swept outside this region the junction became unipolar. In contrast to the Al-Ni junction, in the case of Ni-Ni contacts (for all GNR lengths), the devices showed p-type doping characteristics (one DP). For shorter junctions (W/L_g >1), as shown in Fig. 1a, the two conductance minima in the majority of the studied devices, cannot be resolved and an electron-hole asymmetry in the conductance is still noticeable. Dirac points overlap (or the disappearance of the second Dirac

point) may be explained by the increase in the transfer length (L_T) by decreasing the channel length (L_g) [5].

Since L_T is inversely proportional to GNR sheet resistance (i.e. channel length), at shorter devices sheet resistance is relatively small compared to longer GNR. Therefore, carrier transport is mainly dominated by the graphene underneath Al contact. More investigation still needed to clarify the effect of transfer length on the formation of p-n junctions. At low temperature (~ 15 K), shorter junctions showed staircase conductance (G) with back-gate modulation as shown in Fig.1c. However, longer junctions showed kinks in the I_d-V_{BG} characteristics (see Fig.1d). Staircase conductance at short devices may be attributed to ballistic transport, where the device length (~ 100 nm) is smaller than the mean free path (λ). In ballistic transport regime, conductance is directly proportional to the Fermi wave number [6]. Figure 2 shows the conductance as a function of Fermi wave number ($K_F = (\pi n)^{0.5}$), where n is the induced carrier concentration (extracted from I_d-V_{BG} curve at Fig. 1c). As can be seen, a remarkable conductance plateau for electrons and holes are observed. Our results are, qualitatively, agree with the results of Cleric *et. al* [6]. Furthermore, as shown in Fig. 2, the conductance is limited to a specific value at small K_F (blue arrow and dashed oval) that reflects the residual doping that limits the carrier concentration to be tuned to lower carrier density [6]. In supported graphene-based devices substrate charge impurities act as major scattering centers which greatly affect the mean free path of the charge carriers and make the transport is diffusive rather than ballistic. Indeed, the conductance of our device is much smaller than quantum conductance ($2e^2/h$), such low conductance of our devices is mainly due to the high contact resistance of Al contacts and substrate effect [7]. To clarify this discrepancy, SEM images of some tested devices were taken (see Fig. 3). SEM images showed clear cracks and cuts in GNRs. These cracks occur close to the metal contacts, especially Al-Al (Fig. 3a) and Al-Ni junctions (Fig. 3b). In contrast, we did not observe any of these cracks and cuts in Ni-Ni junctions. This observation suggests that the poor mechanical properties and high linear thermal coefficient of Al (~ $23x10^{-6}/C^o$) introduced uniaxial stress on the GNRs during cooling down, which can generate these kinds of cracks [8]. Cracked GNRs, possibly, have narrow constriction. If the width of the constrictions is comparable to its length the signature of ballistic transport can be observed in back-gate characteristics (I_d-V_{BG}) [9].

3. Conclusions

We demonstrated that graphene p-n junction can be formed by utilizing two different metal-graphene interfaces. Long graphene junction clearly shows two Dirac points, however, they overlapped at shorter junctions. We explained this behavior due to the remarkable increase in the transfer length at the graphene-Al interface. Poor mechanical properties of Al metal generated cracks and constrictions in the GNRs at short and long junctions as well. The formation of narrow constrictions is responsible for the ballistic conductance plateau in short junctions.

Acknowledgements

This work is supported by The Japan Society for the Promotion of Science (JSPS KAKENHI 18F18365).

References

[1] Han, M. Y., et al. (2010). Physical Review Letters 104(5): 056801.
[2] Hammam, A. M. M., et al. (2017). Carbon 121: 399-407.
[3] Giovannetti, G., et al. (2008). Physical Review Letters 101(2).
[4] Song, S. M., et al. (2012). Nano Letters 12(8): 3887-3892.
[5] Xia, F., et al. (2011). Nat Nanotechnol 6(3): 179-184.
[6] Clericò, V., et al. (2019). Scientific Reports 9(1).
[7] Lu, Y., et al. (2010). Small 6(23): 2748-2754.
[8] McRae, A. C., et al. (2019). Physical Review Applied 11(5).
[9] Guimarães, M. H. D., et al. (2012). Physical Review B 85(7).

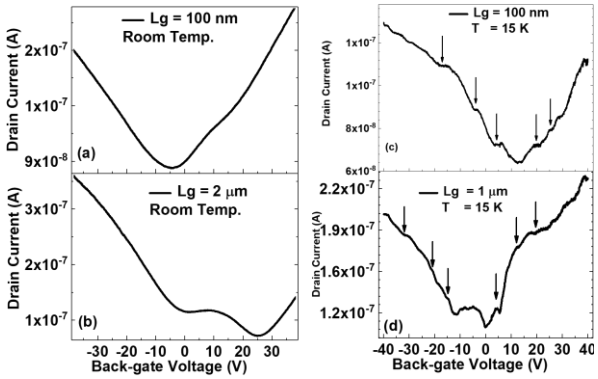

Fig. 1. Back-gate characteristics (Id-VBG) of Al-Ni contacted GNR (a) 100 nm GNR at room temperature (b) 2 μm GNR at room temperature (c) 100 nm GNR at 15 K, (d) 1 μm GNR at 15 K

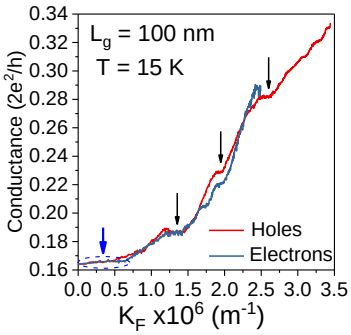

Fig. 2. Conductance G of holes and electrons as a function of the Fermi wavenumber (K_F)at 15 K for 100 nm Al-Ni contacted GNR. Black arrows refer to conductance plateau for both holes and electrons. Blue arrow and dashed oval refer to the conductance limit at small K_F.

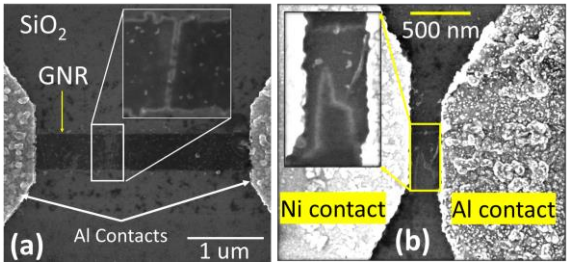

Fig. 3. SEM images of a) Al-Al contacted GNR and (b) Al-Ni contacted GNR. The inset in both images shows the generated cracks in the GNR due to thermal contraction of aluminum contact.