Analysis on Non-Ideal Nonlinear Characteristics of Graphene-Based Three-Branch Nano-Junction Device

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SUMMARY  We investigate the origin of non-ideal transfer characteristics in graphene-based three-branch nano-junction (TBJ) devices. Fabricated graphene TBJs often show asymmetric nonlinear voltage transfer characteristic, although symmetric one should appear ideally. A simple model considering the contact resistances in two input electrodes is deduced and it suggests that the non-ideal characteristic arises from inequality of the metal-graphene contact resistances in the inputs. We fabricate a graphene TBJ device with electrically equal contacts by optimizing the contact formation process and almost ideal nonlinear characteristic was successfully demonstrated.

key words: graphene, TBJ, nonlinear characteristic, contact resistance, graphene-metal contact

1. Introduction

A three-branch nano-junction (TBJ) is a T or Y-shaped tinny three-terminal device. It exhibits unique nonlinear voltage transfer characteristic [1]. This makes a TBJ device, in case with electron carriers, to operate as a two-input AND gate [2], [3]. Graphene is very attractive material for the TBJ, since the polarity of the nonlinear curve can be switched by electric field effect owing to ambipolar transport [4], [5] together with high carrier mobility at room temperature (RT). This suggests that the graphene TBJ can operate as not only AND gate but also OR gate [5]. Furthermore, we recently demonstrated that the graphene TBJ could also operate as a NOT gate [6]. Therefore the graphene has a potential to implement a complete set of logic gates by itself. However, voltage transfer characteristics in the fabricated devices often deviated from the ideal one [4], [6], [8], which deteriorates the logic gate operations. In this paper, we investigate the origin of the non-ideal voltage transfer characteristics in the graphene TBJs. A simple equivalent circuit model is deduced to explain the observed behavior and we point out the effect of metal-graphene contact resistance inequality. Then we experimentally demonstrate that an ideal nonlinear curve can be achieved by forming equal contacts of the two inputs using an optimized metal-graphene contact formation process.

2. Theoretical Model

Basic structure of a graphene-based TBJ together with typical measurement setup is shown in Fig. 1(a). The TBJ has two input branches and an output branch. A back gate controls the carriers in graphene. When the left and right branches are biased in push–pull fashion, \( V_L = V_{bias} \) and \( V_R = -V_{bias} \), the center branch voltage \( V_C \) as a function of \( V_{bias} \) shows a parabolic curve as shown in Fig. 1(b) [7]. The curvature and polarity of curves can be changed by gate voltage \( V_G \), since they depend on carrier density and conduction type, respectively. The basic behavior can be described by an input-electrode capacitor model [6], [7], where the conductance in the two input branches are unequal due to the difference in the induced charge density underneath the two input electrodes. However, experimental curves often obviously incline to left or right. This non-ideal behavior has been considered to arise from the inequality of the contact resistance of the inputs [6].

To understand the observed non-ideal behavior, we consider an equivalent circuit model including the input contact resistances as shown in Fig. 2. In this model, \( V_C \) is simply expressed by

\[
V_C = \frac{(R_- + R_{C-}) - (R_+ + R_{C+})}{(R_- + R_{C-}) + (R_+ + R_{C+})} V_{bias},
\]

where \( R_- \) and \( R_+ \) are resistance values of the negatively and positively biased input branches, and \( R_{C-} \) and \( R_{C+} \) are metal-graphene contact resistance values in the negatively and positively biased input electrodes, respectively. \( R_\text{c} \) and \( R_\text{p} \) are evaluated by the next formulas,

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to 4 contact with large variation of resistivity from 4 in our experiment, PtPd alloy often showed poor ohmic con-
stitution by electron-beam lithography and oxygen plasma etching.

[49x449]V

in polyethylenimine (PEI) for 24 h \[309x59\]Ω

determined by optical contrast \[309x59\]Ω

to 0 V . When \(V_{\text{bias}} \ll V_{\text{G}}\), Eq. (1) is approximately given by the next formula,

\[
V_{\text{C}} \approx \frac{2}{V_{\text{G}}[2+kV_{\text{G}}(R_{\text{C}_+}+R_{\text{C}_-})]} V_{\text{bias}}^2 + \frac{k(R_{\text{C}_-}-R_{\text{C}_+})V_{\text{G}}}{2 + kV_{\text{G}}(R_{\text{C}_+}+R_{\text{C}_-})} V_{\text{bias}}
\]

where \(k = \mu C_{\text{G}} W/L\). In case of \(R_{\text{C}_+} = R_{\text{C}_-} = 0\), we obtain \(V_{\text{C}} = -V_{\text{bias}}^2 / V_{\text{G}}\), which corresponds to the result of the input electrode capacitor model \([6, 7]\) and indicates a symmetric \(V_{\text{C}} - V_{\text{bias}}\) curve as shown in Fig. 1(b). Eq. (3) clearly shows that the symmetry of the \(V_{\text{C}} - V_{\text{bias}}\) curve is broken by the right second term, when the input contact resistances are not the same. Since the right second term is proportional to \(V_{\text{bias}}\), the parabolic \(V_{\text{C}}\) curve simply inclines when \(R_{\text{C}_-} \neq R_{\text{C}_+}\).

3. Comparison with Experiment

Next we investigate the validity of the model and clarify the effect of the contact resistance inequality by comparison with experimentally obtained characteristics in the fabricated graphene TBJ. A graphene sheet was obtained by micromechanical exfoliating graphite and it was transferred on a 90-nm silicon oxide substrate. The monolayer was determined by optical contrast \([10]\). Metal electrode patterns were formed by electron beam lithography, and 40 nm PtPd alloy was deposited by sputtering and lift-off. In our experiment, PtPd alloy often showed poor ohmic contact with large variation of resistivity from \(4 \times 10^{-3} \text{Ωcm}^2\) to \(4 \times 10^{-4} \text{Ωcm}^2\). A T-shape TBJ structure was formed by electron-beam lithography and oxygen plasma etching. In order to shift \(V_{\text{G}}\) to 0 V, the sample was immersed in polyethylenimine (PEI) for 24 h \([11]\). All the measurements carried out at room temperature. Figure 3 shows the measured branch resistances as function of \(V_{\text{G}}\) in the fabricated TBJ device. \(R_{\text{total}}\) was evaluated from the current-voltage, \(I_{\text{total}} - V_{\text{bias}}\), characteristic through the two input branches, which included the graphene branch resistances and the metal-graphene contact resistances in the two inputs. Here \(V_{\text{bias}}\) was applied in push–pull fashion. In this measurement, \(V_{\text{C}}\) was also monitored. Then the left and right branch resistances, \(R_{\text{L}}\) and \(R_{\text{R}}\), respectively, were evaluated by \(R_{\text{L}} = (V_{\text{bias}} - V_{\text{C}})/I_{\text{total}}\) and \(R_{\text{R}} = (V_{\text{C}} + V_{\text{bias}})/I_{\text{total}}\), respectively. Evaluated \(R_{\text{L}}\) included the graphene branch resistance and the metal-graphene contact resistance only in the left input branch. As \(V_{\text{G}}\) increased, both \(R_{\text{L}}\) and \(R_{\text{R}}\) decreased rapidly and saturated. This saturation arose from the contact resistance, since the graphene resistance was sufficiently low. Taking account of this point, observed resistance difference of 3 kΩ between left and right branch resistances in Fig. 3 was considered to be \(\Delta R_{\text{C}} = R_{\text{C}_+} - R_{\text{C}_-}\) for electrons. Unfortunately, we could not estimate \(\Delta R_{\text{C}}\) for hole, because the current saturation was not observed when \(V_{\text{G}} \ll 0\) in this experiment.

Figure 4 compares the experimental and theoretical \(V_{\text{C}} - V_{\text{bias}}\) curves of the graphene TBJ. Theoretical curves are shown for electrons only, because \(\Delta R_{\text{C}}\) for hole could
not be obtained from Fig. 3. The experimental curves obviously inclined and the slope of the incline depended on $V_G$. Using $\Delta R_C = 3 \, \Omega$ for electrons together with other experimentally obtained parameters, $\mu = 5,000 \, \text{cm}^2/\text{Vs}$, $C_G = 3.84 \times 10^{-4} \, \text{F/m}^2$, $L/W = 500 \, \text{nm}/300 \, \text{nm}$, $V_{\text{CNP}} = -0.5 \, \text{V}$, and $\Sigma R_C = R_{C_+} + R_{C_-} = 8 \, \Omega$, the asymmetric nonlinear characteristics in the fabricated device could be reproduced by Eq. (3) very well. This result verified the validity of our model for explaining the non-ideal nonlinear curves. It was found that unequal input contact resistances gave a significant impact on nonlinear voltage transfer curve in the TBJ. Formation of low and uniform metal-graphene contacts is necessary for achieving an ideal voltage transfer characteristic.

4. Impact of Improved Metal-Graphene Contacts

In order to obtain reduced metal-graphene contact resistance reproducibly, we investigated the Ni/Au stack for the metal electrodes. This metal stack is known to provide a low contact resistivity for graphene [9], [12], [13]. In this experiment, the graphene surface was cleaned by annealing at 300°C for 1 h prior to the lithography. Then the metal electrode patterns were formed by electron beam lithography. 10-nm Ni/50-nm Au was deposited via electron beam evaporation and lift-off. Using a cross bridge Kelvin method [9], the Ni/Au electrodes were found to achieve $5 \times 10^{-8} \, \Omega \cdot \text{cm}^2$ in the high carrier density regime, which was comparable to the other reported values [9]. This resistance was much lower than that of the PtPd alloy.

We fabricated the graphene TBJ device with the improved metal-graphene contact formation process. Figure 5(a) shows AFM phase image of the fabricated graphene TBJ. It could show the configuration of the device even covered with a thick PEI layer for surface doping. Each branch had a length of 500 nm and a width of 300 nm. Figure 5(b) shows the measured resistance thorough the input branches. The resistance was evaluated from the current through the two input branches by applying voltage of 0.1 V. Obviously, this resistance was much lower than that of the TBJ. Formation of low and uniform metal-graphene contacts is necessary for achieving an ideal voltage transfer characteristic.

![Image](image.png)

**Fig. 5** (a) AFM phase image of the fabricated TBJ device using optimized contact formation process and (b) measured resistance value through the two inputs.

![Image](image.png)

**Fig. 6** Measured voltage transfer characteristics in the fabricated TBJ with improved metal-graphene contacts.

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On the other hand, $\beta$ from the device with the improved contact was very small and less than 2% was achieved even at $V_G - V_{CNP} = 4$ V. Obtained results clarified a large impact of the uniformity of the metal-graphene contact resistance on the graphene TBJ nonlinear characteristics.

5. Conclusions

We investigated the origin of the non-ideal transfer characteristics in graphene-based three-branch nano-junction (TBJ) device. A simple model considering the contact resistances in two input electrodes was deduced and it could explain the observed behaviors well. The model analysis suggested that the non-ideal characteristic arose from the inequality in the metal-graphene contact resistances of the input branches. We fabricated the graphene TBJ device with almost equal metal-graphene contacts by optimizing the formation process. The fabricated device with the improved contact successfully showed almost ideal nonlinear characteristic.

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References


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