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Effects of Randomly Distributed Local Dirac Points in Graphene Channel on Its FET Transfer Characteristics

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Introduction

Graphene FET is reported to show an extremely high mobility[1]. It is concerned, however, that the perfectly uniform potential distribution in the FET channel is not always assured, since the channel is definitely affected by electrical and mechanical interactions with the dielectric insulator and charged impurities brought in device fabrication. In fact, there have been experimental studies on distributions of Raman G band[2] or Dirac Point (DP) in the channel[3].

This paper discusses effects of randomly distributed DPs in the graphene channel on its FET characteristics, in terms of i) the conventional 4-probe measurements on graphene FET in many local positions, and ii) the resistor network calculation for simulating the channel inhomogeneity.

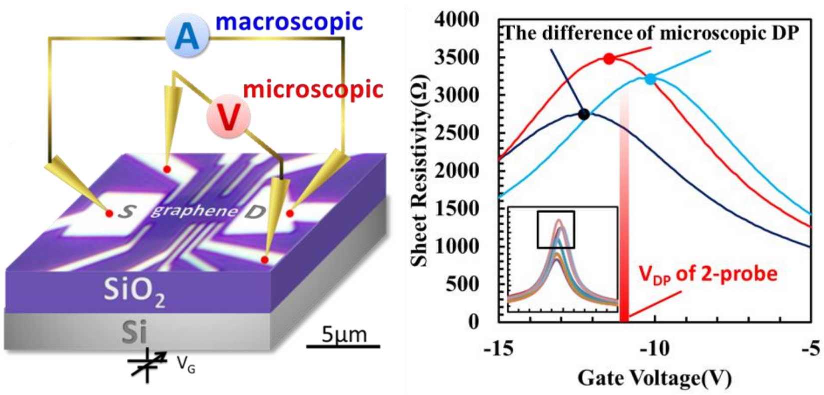
i) 4-probe measurements

Graphene was mechanically exfoliated from Kish graphite onto 90-nm SiO_2/p^+-Si substrates. The number of layers was determined by the optical contrast and Raman spectroscopy. Electron-beam lithography was utilized to pattern electrical contacts onto graphene, and each contact area for the voltage probe was as small as possible, ~300x600 nm, in case the contact affected the channel properties in itself. The contact metals of Cr/Al (~10/20 nm) were thermally evaporated on the resist-patterned graphene in a chamber at 10^{-3} Pa, followed by the lift-off process. The 4-probe measurements, as shown in **Fig. 1(a)**, were performed in a vacuum at 10^{-3} Pa with a source-drain bias (V_{ds}) of 10 mV.

Fig. 1(b) clearly shows that the local DP differs from position to position. The longer distance between two voltage probes makes the difference between macroscopic and microscopic DPs smaller. This fact is an experimental evidence for inhomogeneous graphene channel on SiO_2. Although the graphene channel is expected to be intrinsically homogeneous except around vacancies or edges, we think it may become inhomogeneous in the device fabrication steps.

ii) Resistor network analysis

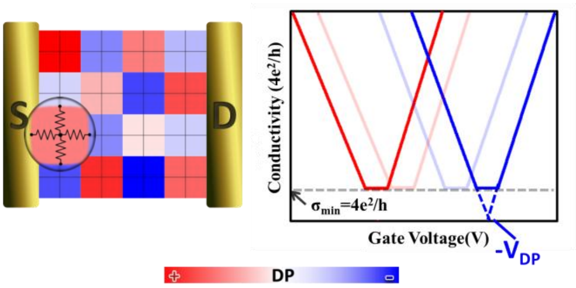
A simple resistor network model was employed for simulating the graphene channel. The network consists of 4x4 resistor segments and each segment includes 4 equivalent resistors in a cross shape, as shown in Fig. 2(a). This model makes it possible to connect a segment to neighboring one via one resistor and to introduce the quantum resistance into the boundary of two adjacent ones (**Fig. 2(a)**). A position dependent



(a) (b)

Fig. 1 (a) Schematic of multiple-probe graphene FET device for 4-probe measurements. The current between source and drain monitors the macroscopic characteristics of a whole channel, while voltage probes monitor a microscopical area of the channel. (b) The difference of microscopic DP ~2V is shown in.

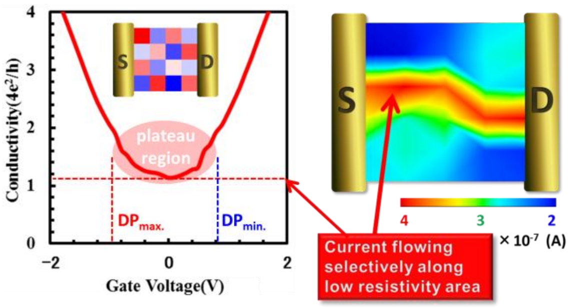
DP value can be put in each segment. By assuming that the mobility (μ) is not dependent on gate bias (V_g), nor on position in the channel, the segment resistance only depends on carrier density (n), which can be calculated using following equations, $R=\rho L/W$, $\rho=1/en\mu$, $n=C_{ox}|V_g-V_{DP}|/e$. Therefore, each segment resistor shows a linear and ambipolar characteristic with gate bias (**Fig. 2(b)**). Then, we can calculate the influence of randomly distributed local DP on macroscopic FET transport characteristics. In addition, we have taken account of quantum resistance $R_Q=h/4e^2\approx 6.45$ kΩ for the resistor at the charge neutrality point $|V_g-V_{DP}|\approx 0$ as the minimal conductivity (σ_{min}). This also means that R_Q should be added to the segment resistance when carriers are transferred from n-type to p-type (or vice versa) between adjacent segments. It is noted we will not discuss the minimal conductivity origin in graphene here, which was discussed also by using the resistor network model for the puddle transport in terms of mesoscopically inhomogeneous channel[4].



(a) (b)

Fig. 2 (a) Schematic of resistor network model. A channel is divided into 4x4 segments. Each of them has 4 equivalent resistors in a cross shape. (b) We assumed symmetry and ambipolar I-V characteristics about $-V_{DP}$ for each segment.

First, we confirmed macroscopic ambipolar I-V characteristics of FET when all segments have the same DPs. The result was, of course, the same as I-V characteristics of the single segment. Second, we considered an inhomogeneous channel, in which each segment has a randomly distributed DP by using the random number table. **Fig. 3(a)** shows σ-V_g characteristics. The most important consequence is that the plateau is seen in a wider region, although each unit has symmetrical and ambipolar characteristics. In addition, the width of the plateau region corresponds to the maximum difference in DP



(a) (b)

Fig. 3 (a) I-V characteristics of the inhomogeneous channel; DP is given by the random number table; -1V~1V. (b) Near the macroscopic DP, current flow path was formed mainly along the low resistivity area, like percolation conduction.

given by the random number table. Also the minimal puddle conductance is not R_Q but around R_Q. It is quite reasonable when R_Q is defined to be the lowest conductance in the homogeneous graphene channel. This fact is also confirmed by looking at the current flow pattern at V_g~V_{DP}. **Fig. 3(b)** shows the percolation type current conduction in the channel. The current flows selectively along the path with the lowest resistance.

Conclusion

From both experiments and calculations, it is concluded that homogeneous transport properties are not always available in the graphene channel. In the experiments, the inhomogeneity in the channel should be taken into consideration for quantitative transport analysis. Furthermore, the simple analytical calculation tells us that without the channel inhomogeneity consideration the understanding of the puddle transport analysis near the Dirac Point might be misled.

The present study does not intend to clarify the mesoscopic mechanism in graphene transport characteristics, but suggests that the view of inhomogeneous graphene channel is required for considering the graphene transport analysis.

Acknowledgements

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