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Gap Width Dependence of Transport through Quantum Point Contact in hBN/Graphene/hBN in the Quantum Hall Regime

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Abstract

We investigate unique electron transport in hBN/graphene/hBN with a quantum point contact (QPC) formed by electrostatic control from a pair of split gates. Especially, it is focused on the QPC gap width dependence of quantized electron transport control by manipulating the edge channel configurations around QPC. The quantum Hall filling factors are allocated in the V_{TG}-V_{BG} mapping of resistance across QPC, and the stepwise changes in resistance were found totally different from what are expected from the filling state configurations in top-gated and bulk regions. It is discussed that the obtained slope of boundaries in the V_{TG}-V_{BG} mapping is determined by the partially open/close configurations of the QPC, which is decisively evidenced by the QPC gap width dependence of the slope.

1. Introduction

Graphene is a two-dimensional sheet of carbon atoms arranged in a honeycomb lattice and possesses extraordinary properties [1,2] such as the unique quantum Hall edge channels in the quantum Hall regime. The quantum Hall effect is a phenomenon which takes place in a 2-dimensional electron gas (2DEG) when a strong perpendicular magnetic field is applied at low temperature, in which the current flows only at the edge of the sample due to the Landau quantization. Graphene exhibits unique edge channel configuration of coexisting electrons/holes edge modes along a p-n junction when graphene is applied with local electrostatic control of the filling states by a local gate [3,4]. Since quantized charge transport in the edge channel is free from energy dissipation, it is one of the promising candidates for a building block for the future low-power consumption information processing devices.

In this paper, we report a unique carrier transport through an hBN/graphene/hBN heterostructures based- quantum point contact (QPC) formed by electrostatic control of a pair of split gates in the quantum Hall regime. Electron conduction across the QPC is determined by the quantum Hall edge channel configuration around the QPC which is controlled electrostatically from both back and top gates between open and close states for the edge channels as shown in Fig 1(b). Here, we investigate the influence of the QPC device structure on the device operation, especially the effect of QPC gap width on the open/close manipulation of edge channels around the QPC.

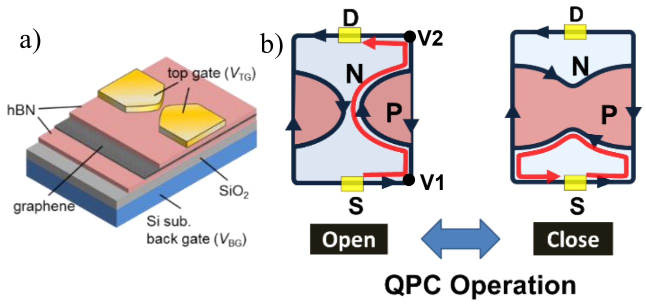

Fig. 1 (a) Schematic of the fabricated device with split gate. (b) Open and close configurations in the QPC device operation. Arrows indicate the direction of the quantum Hall edge channels.

2. Device Fabrication and Measurement

Graphene and hBN layers were prepared using simple mechanical exfoliation method. The stacking of this heterostructures on Si wafer with a 90-nm-thick silicon dioxide (SiO_2) layer can be realized with an improved process called all-dry transfer process. This process can prevent graphene from getting in contact with any processing-chemicals [5,6]. A layered structure of a single layer graphene sandwiched by hBN with a dimension up to 10 µm has been successfully fabricated. In this work, two hall bars equipped with 6 edge contacts [7] and split gates of 60 and 120 nm gap located in the center forming QPC devices were fabricated on clean and bubble free area of the hBN/graphene/hBN layers. Filling states in graphene is controlled by top-gate bias (V_{TG}) and back-gate bias (V_{BG}). Longitudinal differential resistance, R_L, was estimated by measuring voltage difference between V1 and V2 with a constant current of 10nA and frequency of 17 Hz between source (S) and drain (D) as shown in Fig. 1(b) by the lock-in measurement technique, at low temperature of 6 K and under perpendicular magnetic fields up to 6 T.

3. Results and Discussion

The high quality of the fabricated devices was confirmed by the high carrier mobility of 115,000 $cm^2/(Vs)$ (electron) and 195,000 cm^2/Vs (hole). The quality of the devices also proven by the detection of filling state, $\nu = \pm 1$ which confirmed the resolved degeneracy of 4-fold Landau quantization due to the hBN/graphene/hBN sandwiched structure. It is worth noting that, the quantum conductance exhibits more number of states when four-fold degeneracy of Landau levels is resolved than in the case of degenerated Landau levels in graphene on SiO_2 [8].

Figure 2 is a typical R_L-V_{TG} curve at V_{BG} = 3.3 V in the 60 nm gap device in which many quantum Hall plateaus appeared. The full V_{TG}-V_{BG} mapping of R_L of the 60 nm and 120 nm gap devices are presented in Figs. 2(b) and (c), respectively. Here, V_{BG} defines the quantum Hall filling states in the bulk region (ν_{bulk}), while V_{TG} as well as V_{BG} define that of the top gated region (ν_{gate}). In Figs. 2(b) and (c), inclined thin solid black lines, indicating the boundaries of different ν_{gate} states, were determined from the V_{TG}-V_{BG} mapping under zero magnetic field. This slope is apparently different from that of the observed boundaries shown in the mapping in Figs. 2(b) and (c), which are indicated by thick red lines. The origin of these observed boundaries can be understood as follows. In the QPC device operation, the constriction of the QPC can be changed between open and close configurations (Fig. 1(b)) by simply changing the top-gate voltage. Here, there exit many edge modes at the QPC, which are in partially open/close configuration, and they show such open/close action successively as the top-gate voltage is changed, resulting in the series of stepwise changes in R_L as shown in the Figs. 2(a).

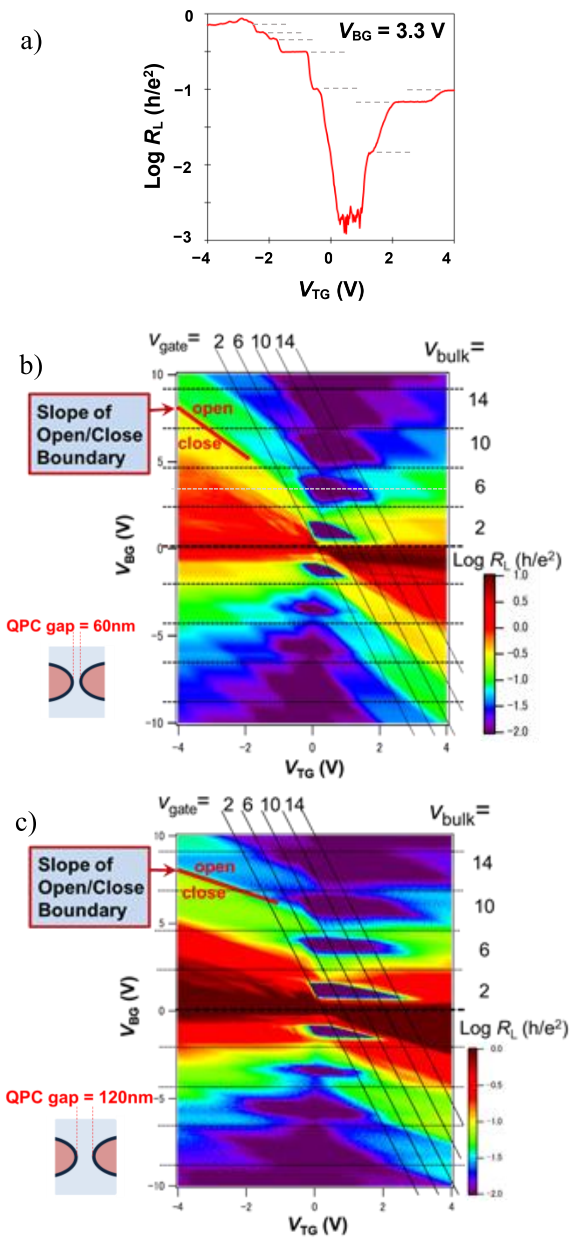

Fig. 2 (a) V_{TG} dependence of R_L at V_{BG} = 3.3V in the 60 nm gap device. A V_{TG}-V_{BG} mapping of R_L of QPC device with gap width of b) 60 nm and c) 120 nm. A white broken horizontal line in (b) corresponds to the data in (a).

By comparing the slopes of 60 and 120 nm gap devices (Figs. 2(b) and (c), respectively), it is found a clear difference of the inclination of the slope of the open/close boundary. The slope for the 60 nm gap device is relatively closer to that of the ν_{gate} line as compared to the 120 nm gap device. This difference in the slope is considered to be originated from the gap width of the QPC structure, reflecting that the difference in the potential ratio between top-gated region and the center of QPC is much larger in the 120 nm device than that of 60 nm one. In other words, this difference in the slope of the boundaries proves the successive open/close operation of the edge modes at the QPC by changing the gate bias.

Conclusions

High quality hBN/graphene/hBN QPC devices were successfully fabricated with different QPC gaps, and their device operation of open/close manipulation of edge channels was demonstrated. We found the strong dependence of the QPC gap width on the open/close manipulation of edge channels at the QPC. The obtained results provide a new insight into graphene nanoelectronics towards the application to the dissipation less information technology.

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