Quantum Hall Transport across Monolayer-Bilayer Boundary in Graphene

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Abstract. Magnetotransport across monolayer-bilayer boundary on a graphene piece has been studied in the quantum Hall state. The edge channel transport in monolayer-bilayer junctions has been discussed based on the Landauer-Buttiker picture following p-n bipolar junctions of monolayer graphene. We considered two extreme cases of transmission from input edge channels to output channels at the junction, the maximum transmission model and the full-mixing model. They give different two-terminal conductance as a function of carrier filling. We measured the two-terminal conductance in monolayer-bilayer junction devices, and the measured conductance agreed better with the full-mixing model. This result suggests that edge channels of monolayer and bilayer regions are almost fully mixed up at the monolayer-bilayer boundary.

1. Introduction: Quantum Hall transport in the p-n bipolar junction of graphene

In the graphene p-n bipolar junctions, the remarkable magnetotransport features have been observed in the quantum Hall state [1]. The two-probe conductance across the p-n junction shows fractional quantization. In addition to the single p-n junction, quantum Hall transport in p-n-p (or n-p-n) double junctions have been also studied [2, 3]. These samples are graphene FET devices with additional top gate electrode which partially covers the sample. The carrier filling of the top-gated region can be changed independently from the rest region. In graphene, the carrier filling can be controlled from electron-filling (n-type) to hole-filling (p-type), so that the p-n bipolar junction can be realized along the boundary between the top-gated part and the other part.

Under high magnetic fields, the n-type and p-type regions show electron-type and hole-type half-integer quantum Hall effect, respectively. Generally, in the quantum Hall state, the Fermi energy is located in the mobility gap between extended states of Landau levels, and the quantum Hall state is characterized by its plateau index, more precisely, the Chern number (the Thouless-Kohmoto-Nightingale-den Nijs number) [4]. This topological number is stable as long as the Fermi level exists in the mobility gap. When the system undergoes transition from one Hall plateau to another one with the change of external parameter such as magnetic field, in other words, when the topological number switches to another one, the Fermi level must pass through the extended states between mobility gaps. We apply this principle to the graphene p-n junction regarding the space position as the parameter. Since the topological number discontinuously changes at the boundary, there should exist one-dimensional extended states (metallic states) along the boundary. We call them the boundary states or the boundary channels.
Generally, quantum Hall transport can be explained as edge channel transport developed by Landauer and Buttiker [5]. In the quantum Hall state of graphene p-n junctions, the n-type and p-type regions have the edge channels with opposite chirality, namely, opposite propagation direction. So as to conserve the current at the edge points of the boundary, the boundary channel must carry the current, so that it is considered that the boundary channel has chirality in the same way as the edge channel. In fact, if edge channels surround both regions independently without any mixing at the boundary, they run in the same direction along the boundary. These chiral edge channels mix up forming the chiral boundary channels.

The fractional quantization of conductance in the graphene p-n junction [1] was well explained in terms of Landauer-Buttiker formalism by assuming the full mixing of n-type and p-type edge channels at the boundary [6]. The edge channels in n-type and p-type regions join together at the edge point of the boundary. Carriers enter to the boundary states and propagate along the boundary. At the other edge point of the boundary, the carrier flow diverges into edge channels in n-type and p-type regions. Here, it is assumed that carriers flow into all output edge channels with the same probability. Under this assumption, the two-terminal conductance across the boundary is given by

$$G^{(p-n)} = \frac{e^2}{h} \left| \frac{\nu_1 \nu_2}{\nu_1 + \nu_2} \right|.$$  \hspace{1cm} (1)

Here, \( \nu_1 \) and \( \nu_2 \) indicate the quantum Hall indices of n-type and p-type regions, respectively. This formula agreed with the experimental result [1] very well.

In the present work, we have studied the quantum Hall transport in another graphene junction structure, the monolayer-bilayer hetero-junction, that is, the monolayer step on graphene. This structure is often observed on graphene flakes on the substrate. The quantum Hall transport in this junction system has also been studied by Zhao, Koshino, and Kim [7]. In below, we discuss possible scenarios on the edge channel mixing at the monolayer-bilayer boundary based on the Landauer-Buttiker formalism, and then, we compare them with our experimental results.

2. Model: Quantum Hall transport in the monolayer-bilayer graphene hetero-junction

We consider the monolayer-bilayer junction system of graphene illustrated schematically in Fig. 1. Two electrodes are located both in the monolayer side and in the bilayer side, and a single monolayer step exists between them. The carrier density in both sides is controlled by the common back-gate voltage, so that carrier numbers in both sides are equal. The filling factors in both sides are also equal.

![Figure 1](image_url)

**Figure 1.** Schematic diagram of monolayer-bilayer junction of graphene. There are \( n \) edge channels in the monolayer region and \( m \) edge channels in the bilayer region. Along the boundary, one-dimensional metallic channels is formed.
Figure 2. Two-terminal conductance of monolayer graphene (broken line), bilayer graphene (dotted line), and monolayer-bilayer junction (solid line) in the quantum Hall state as functions of the filling factor. Spin and valley degeneracy is included.

under magnetic fields. Although monolayer and bilayer graphene exhibit quantum Hall effect, it appears at different filling factors with different plateau values: The plateaus appear around filling factors of $n=\pm 2, \pm 6, \pm 10, \ldots$ with plateaus values $\sigma_{xy}=-\frac{e^2}{h} n$ in monolayer, and around $m=\pm 4, \pm 8, \pm 12, \ldots$ with $\sigma_{xy}=-\frac{e^2}{h} m$ in bilayer. This difference originates from different degeneracy of the $n=0$ Landau level. In below, we consider the situation where the monolayer side and the bilayer side show the quantum Hall effect simultaneously. This situation is expected when the transition regions between the quantum Hall states are narrow enough in both sides.

In order to discuss the quantum Hall transport across the monolayer-bilayer junction, we employ the similar logic as that used for the p-n junction mentioned above. The quantum Hall states of the monolayer and bilayer regions have different Chern topological numbers $n$ and $m$, which never become equal. So, there must exist one-dimensional metallic states along the boundary between two quantum Hall regions. We call them the boundary states or the boundary channels following the p-n junction. However, contrary to the case of the p-n junction, the edge channels of the monolayer and bilayer regions have the same chirality, namely, the same propagation direction as shown in Fig. 1. Since both regions have different numbers of edge channels $n$ and $m$, the boundary state must carry the current so as to conserve the current at two edge points of the boundary. In this case, however, it is considered that the boundary channels do not have the same chirality. If edge channels surround both regions independently without any mixing at the boundary, they run in the counter direction along the boundary. So, the boundary channels must carry the current in both directions.

We consider two-terminal conductance across the monolayer-bilayer boundary in the quantum Hall state in terms of the Landauer-Buttiker picture. At the lower (upper) edge point of the boundary in Fig. 1, $n$ channels of monolayer ($m$ channels of bilayer) enter into the boundary and $m$ channels of bilayer ($n$ channels of monolayer) leave the boundary. As the detail of carrier transmission from each input channel to each output channel is unclear, here, we consider two extreme cases. In the first case, we assume the maximum transmission from input channels of monolayer (bilayer) to output channels of bilayer (monolayer) at the lower (upper) edge point of the boundary. In this model, two-terminal conductance across the boundary takes the maximum value:

$$G^{(\text{monolayer-bilayer})} = \frac{e^2}{h} \min(n,m).$$

(2)
So, the even-integer plateau values are expected. In the second case, we assume full-mixing of edge channels at the boundary in the same way as the p-n bipolar junctions. In this model, it is assumed that electrons injected from all input channels flow out to all output channels with the equal probability. The two-terminal conductance is given by the same formula as p-n junctions:

\[
G^{\text{(monolayer-bilayer)}} = \frac{e^2}{h} \left| \frac{\nu_l \nu_r}{\nu_l + \nu_r} \right|
\]

(3)

Figure 2 shows the filling factor dependence of the two-terminal conductance of the monolayer-bilayer junction in the quantum Hall state. The maximum transmission model gives lower plateaus of monolayer and bilayer indicated by dashed lines. The full-mixing model gives fractional plateaus indicated by solid lines. Note that the gate-voltage dependence has different slope in two cases.

3. Experimental confirmation

We have performed the magnetotransport measurement of monolayer-bilayer graphene junctions. Graphene pieces have been prepared from Kish graphite by mechanical exfoliation technique on SiO$_2$/n-Si substrate, which works as a back-gate electrode in FET devices. Graphene pieces with monolayer-bilayer boundary were picked up and electrodes were fabricated on them using electron-beam lithography technique. The graphene thickness was checked by the micro-Raman measurement. The microscope image of the typical device is shown in the inset of Fig. 3.

Figure 3 shows the two-terminal conductance measured by $e^2/h$ across monolayer-bilayer boundary at $B=10$T and $T=4.2$K. A few fractional plateau values given by eq. (3) are indicated by dashed lines. As a function of the gate voltage, two-terminal conductance increases almost linearly with weak oscillatory (plateau-like) modulation, which corresponds to the transition between different quantum Hall states. Its slope agrees with that predicted by the full-mixing model much better than the maximum transmission model. Since the perfect quantum Hall states are not realized over the whole gate voltage range in the experiment, the data has not sharp staircase shape but rather smeared one.

![Figure 3. Back-gate-voltage dependence of two-terminal conductance across the monolayer-bilayer junction. Inset shows the microscope image of the graphene FET device with monolayer-bilayer junction indicated by broken line.](image-url)
Nevertheless, the observed plateaus are in the same order of fractional values (4/3, 12/5, 24/7) expected from the full-mixing model. They are hardly explained as even integers deduced from the maximum transmission model. Therefore, the experimental result seems to support the full-mixing of edge states of monolayer and bilayer regions at the junction more strongly than the maximum transmission of edge states.

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