

## Observation of chiral quantum-Hall edge states in graphene

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In this study, we determined the chiral direction of the quantum-Hall (QH) edge states in graphene by adopting simple two-terminal conductance measurements while grounding different edge positions of the sample. The edge state with a smaller filling factor is found to more strongly interact with the electric contacts. This simple method can be conveniently used to investigate the chirality of the QH edge state with zero filling factor in graphene, which is important to understand the symmetry breaking sequence in high magnetic fields ( $\geq 25$  T). © 2009 American Institute of Physics. [DOI: 10.1063/1.3123265]

At a quantum-Hall (QH) plateau in a two-dimensional (2D) electron system, conducting electrons in the QH edge states circulate in one direction (a chiral direction) without any dissipation.<sup>1-3</sup> These QH edge states can be conveniently used to build quantum devices such as a solid-state electronic beam splitter.<sup>4</sup> In graphene, a honeycomb lattice of  $sp^2$ -bonded carbon atoms, the relativistic character of the Dirac-fermionic carriers exhibits the half-integer QH effect,<sup>5</sup> which is distinctive from the integer QH effect in ordinary 2D electronic systems.<sup>1</sup> It has been generally believed that carriers in the QH edge states in graphene also circulate in one direction (one chirality), either clockwise or counterclockwise, as in a conventional 2D electron gas for a fixed perpendicular magnetic field.<sup>6-8</sup> The chiral properties of the QH edge states are important, in particular, in a strong-enough magnetic field as to break either the spin or pseudospin symmetry, which leads to the QH plateau of zero filling factor.<sup>9-13</sup> Depending on whether the spin or the pseudospin symmetry is broken first, graphene becomes either ferromagnetic or insulating, respectively.<sup>14,15</sup> In the QH ferromagnetic state,<sup>9-11</sup> the QH edge carriers in the zero plateau are believed to be in a counter-circulating state, but in the QH insulating state,<sup>12,13</sup> the edge states themselves do not exist.

In this study, we examined the chiral direction of the QH edge states in graphene by using a simple two-terminal transport measurement scheme while grounding different edge positions of the sample. Reduction and recovery of the conductance were observed depending on the position of the grounded edge contacts (ECs), on the back gate (BG) voltage ( $V_{BG}$ ), and on the magnetic-field direction. Our study indicates that the QH edge states in graphene also possess the chirality,<sup>2,3,16</sup> and, moreover, the edge states corresponding to smaller filling factors are more strongly coupled with the electrical contacts.<sup>17</sup>

Monolayer graphene sheets were mechanically exfoliated<sup>18</sup> onto a highly doped silicon substrate covered with a 300-nm-thick oxidation layer, where the substrate served as the global BG. The device [Fig. 1(a)] was fabricated by the sequential e-beam lithography and the electrode metallization by evaporation.<sup>19</sup> The sample was cooled down

to 120 mK in a dilution fridge (Oxford Instruments, Model Kelvinox), where electric noises were filtered out by connecting low-pass  $RC$  and  $\pi$  filters in series.<sup>19</sup> At the base temperature, the two-terminal conductance ( $G=I/V_{SD}$ ) was measured using the conventional lock-in technique operated at 13.33 Hz while monitoring the current with a current pre-amplifier for the source-drain bias voltage ( $V_{SD}$ ) of 30  $\mu$ V. The measurement configuration is illustrated in Fig. 1(a).

Figure 1(b) shows the electric-field control of the conducting charge carriers,<sup>5</sup> which reveals a resistance maximum at  $V_{BG} \sim 3.8$  V. At this charge neutrality point ( $V_{CNP}$ ), the carriers change from being holelike to being electronlike with increasing  $V_{BG}$  [see the inset of Fig. 1(b)].<sup>5</sup> As shown in Fig. 1(b), the resistance asymmetry is present between the hole and the electron sides, i.e., the mobility ( $\mu$ ) of the device differs as the carrier type varies. The value of  $\mu$  is  $\sim 3600$   $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$  ( $\sim 4500$   $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ ) for  $V_{BG}=30$  V ( $-20$  V). This electron-hole asymmetry may arise from the unintended chemical doping of the graphene sheet in the fabrication process<sup>20</sup> or the charge pinning at the interface of invasive metallic contacts and the graphene sheet.<sup>21</sup>

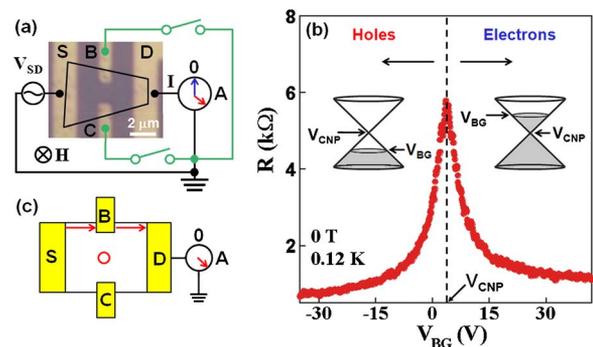


FIG. 1. (Color online) (a) An optical microscopic image of the sample and the measurement configuration (the scale bar represents 2  $\mu\text{m}$ ). The black lines represent the boundary of the graphene. Switches connected to the EC electrodes are used to control grounding the electrodes B and C. The current is measured at the drain D. (b) The BG voltage ( $V_{BG}$ ) dependence of the resistance in zero magnetic field, which illustrates a bipolar electric field effect. Inset: energy-momentum dispersion relations in the hole side;  $V_{BG} < V_{CNP}$  (left) and in the electron side;  $V_{BG} > V_{CNP}$  (right). (c) Schematic configuration of the clockwise QH edge-state circulation in the hole side at positive  $V_{SD}$  with no grounded ECs.

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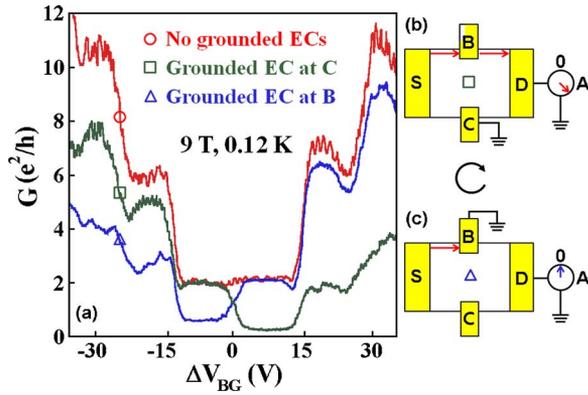


FIG. 2. (Color online) (a) Two-terminal conductance ( $G$ ) as a function of a BG voltage difference ( $\Delta V_{BG} = V_{BG} - V_{CNP}$ ) in 9 T. Open circle: no grounded ECs. Open square: the EC grounded at C. Open triangle: the EC grounded at B. (b,c) Schematic configurations of the clockwise QH edge state circulation (for hole side and positive  $V_{SD}$ ) corresponding to the recovery and the reduction of  $G$ , respectively, in conductance plateaus.

Figure 2(a) displays the two-terminal conductance  $G$  in units of  $G_0 = e^2/h$  as a function of  $V_{BG}$  with respect to  $V_{CNP}$  ( $\Delta V_{BG} = V_{BG} - V_{CNP}$ ) measured in  $H = 9$  T [see Fig. 1(a) for the positive field direction]. The total contact resistance including the resistance of low-pass RC filters connected in series,  $\sim 4.3$  k $\Omega$ , was obtained independently and subtracted from the measured two-terminal conductances. With the EC electrodes B and C being floated, a clear conductance plateau at  $2G_0$  is observed in the region of  $\sim -15$  V  $< \Delta V_{BG} < \sim 15$  V (open circle). Moreover, the clear plateaus at  $6G_0$  and  $\sim 10G_0$  in the hole side ( $\Delta V_{BG} < 0$ ) indicate the occurrence of the half-integer QH effect, which confirms the single layeredness of our graphene sheet.<sup>7,8,22,23</sup> The distorted  $\sim 6G_0$  and  $\sim 10G_0$  plateaus in the electron side ( $\Delta V_{BG} > 0$ ) are believed to arise from the reduced zero-field mobility of our graphene sheet in the electron side [Fig. 1(b)]. Similar distortion of the two-terminal conductance has been suggested<sup>22</sup> and experimentally confirmed as well.<sup>23</sup>

As denoted by the open square symbol in Fig. 2(a), the conductance plateau at  $2G_0$ , with the EC grounded at the electrode C, remains unaltered for  $\Delta V_{BG} < 0$  (the hole side) while it vanishes almost completely for  $\Delta V_{BG} > 0$  (the electron side). On the contrary, the open-triangle data, which were obtained with the EC grounded at B, show a significant reduction of the conductance in the hole side while the conductance in the electron side recovers the value without grounded ECs. The reduction of the conductance occurs as the conducting carriers are leaked to ground before they reach the drain (D) where the current detector A is located [Fig. 1(a)]. Thus, the result in Fig. 2(a) clearly indicates that the holelike and the electronlike carriers in the edge states of QH plateaus circulate in the opposite directions with each other. To further confirm our reasoning, we measured  $G$  in a negative magnetic field ( $-9$  T), as shown in Fig. 3(a), with the contact resistance being subtracted. With no grounded ECs, the open-circle data show almost the same feature as the corresponding open-circle data in Fig. 2(a), along with distorted QH plateaus in the electron side. However, the open square (triangle) data nearly coincide with the open triangle (square) data in Fig. 2(a). This indicates that the reduction and recovery of  $G$  depend on the position of the grounded EC, the carrier type, and the magnetic field direction.

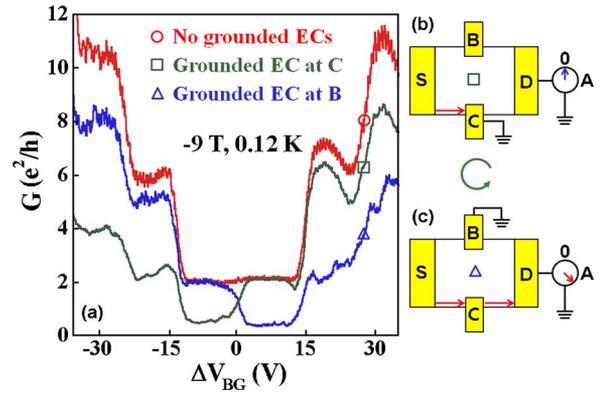


FIG. 3. (Color online) (a) Two-terminal conductance ( $G$ ) as a function of a BG voltage difference ( $\Delta V_{BG} = V_{BG} - V_{CNP}$ ) in  $-9$  T. Open circle: no grounded ECs. Open square: the EC grounded at C. Open triangle: the EC grounded at B. (b,c) Schematic configurations of the counterclockwise QH edge state circulation (for hole side and positive  $V_{SD}$ ) corresponding to the reduction and the recovery of  $G$ , respectively, in conductance plateaus.

The observed reduction and recovery of the conductance can be explained by assuming that the chiral property of the QH edge states in graphene is the same as the one in an ordinary 2D electron gas.<sup>2,3</sup> As illustrated in Fig. 1(c), holes (electrons) in graphene in QH plateaus flow along the upper side of the sample between the source (S) and the drain (D) in a positive (negative) magnetic field, which corresponds to the *clockwise* QH edge state. For simplicity, schematics of the QH edge state circulation are illustrated in the figures only for the hole side at a positive  $V_{SD}$ . Consequently, with no grounded ECs, charge carriers are not impeded until they reach the drain D, so that  $G$  becomes the Hall conductance as shown by the open-circle symbols in Figs. 2(a) and 3(a).<sup>3,7,8,22,23</sup> On the other hand, if a grounded EC is placed in the way of the QH edge state circulation between S and D, electric charges are diverted to ground before they reach D. The consequent vanishing of current leads to the reduction of the conductance, as illustrated in Figs. 2(c) and 3(b) for the *clockwise* and *counterclockwise* QH edge states, respectively. By contrast, if an EC is grounded in the opposite side of the sample in the circulation path, the current is not drained to ground before reaching the drain D, resulting in the recovery of the conductance as illustrated in Figs. 2(b) and 3(c).

Up to this point, we assume that conducting carriers are always emitted from the source S, i.e., a positive (negative)  $V_{SD}$  for hole (electron) carriers. But, if hole (electron) carriers are emitted from both D and the grounded EC for a negative (positive)  $V_{SD}$ , the conductance reduction occurs as the same amount of holes (electrons) enter into and leave from D simultaneously with vanishing current  $I$ . Thus, the results in Figs. 2(a) and 3(a) directly confirm that the QH edge states in graphene also behave in the same way as those in an ordinary 2D electron gas, whose chiral direction depends on the carrier type and the magnetic field direction.<sup>2,3</sup>

The imperfect reduction and recovery of  $G$  are seen in Figs. 2(a) and 3(a) for  $\Delta V_{BG} > 15$  V and  $< -15$  V, which suggest that the coupling strength between the electric contacts and the QH edge states is not uniform for different filling factors.<sup>17</sup> It is because the QH edge states with smaller filling factors circulate closer to the edge of a sample,<sup>2,3</sup> with stronger coupling with the electric contacts near the edge. Therefore, a fraction of carriers in the QH edge states with higher filling factors of 6 and 10 either reach the drain D by

passing the grounded EC in the way of the carrier circulation (corresponding to the imperfect reduction) or are drained at the grounded EC in the path after passing the drain D (corresponding to the imperfect recovery). The coupling is expected to be stronger for a larger contact area of the ECs, which explains why the conductance  $2G_0$  shows the full recovery but with the imperfect reduction.

In summary, we made simple two-terminal conductance measurements to clarify the chiral properties of the QH edge states in graphene, which is important to design delicate functionalities in graphene-based quantum devices. Experimental findings directly support that the QH edge states in graphene are chiral in the same way as those in an ordinary 2D electron gas in low magnetic fields<sup>2,3,16</sup> ( $\sim 9$  T). In addition, from the imperfect reduction and recovery observed in the experiment, we demonstrate that the coupling strength between the QH edge states and the electric contacts varies depending on the filling factors as well as the contact area.<sup>17</sup> This simple two-terminal conductance-measurement scheme can be conveniently adopted to study the chiral direction of the QH edge state of zero filling factor in graphene in a stronger magnetic field<sup>9-13</sup> ( $\geq 25$  T), to clarify the quantum state between the two contradicting models leading to the QH ferromagnets and the QH insulators.<sup>14,15</sup>

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