Observation of quantum Hall effect in mono- and bi-layer graphene using pulse magnet

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Abstract. We report on the magnetotransport measurements of mono- and bi-layer graphene in pulsed magnetic fields up to $B = 53$ T. In a mono-layer graphene, the Hall resistance $R_{H}$ is quantized to $R_{H} = \left(\frac{h}{e^2}\right) \nu^{-1}$ with integer values $\nu = 2, 6, \text{ and } 10$ for either hole or electron doping. In a bi-layer graphene, $R_{H}$ is quantized to $R_{H} = \left(\frac{h}{e^2}\right) \nu^{-1}$ with $\nu = 4, 8, \text{ and } 12$. These results indicate that the precise magnetotransport measurements of the graphene can be conducted in the environment of pulse magnetic fields.

1. Introduction

The pulsed high magnetic field technique has been an effective experimental tool for the studies of the integer and fractional quantum Hall effect (QHE) in conventional semiconductor two-dimensional electron systems [1-3]. This is because strong magnetic fields $B \sim 730$ T can be obtained by using the pulse magnet [4] whereas the static magnetic fields are limited to $B \sim 45$ T. During the past few years, the QHE in mono-layer and bi-layer graphene have been attracting considerable interest [5-7]. In a mono-layer graphene, the charge carriers have a linear energy spectrum and show Berry’s phase of $\pi$. The Landau quantization of those carriers in high magnetic fields results in the half-integer QHE with the shifted positions of the quantum Hall plateaus [6]. In a bi-layer graphene, its parabolic band structure and the chiral nature of charge carriers result in the integer QHE but the zero-level energy gap missing [8]. Recently, by using the static high magnetic field techniques, the lifting of valley and spin degeneracy of the Landau levels and the fractional QHE were reported [9-12]. For the further studies of the QHE in higher magnetic fields, it is of great importance to establish the measurement techniques for the QHE in graphene using pulse magnet.

In this work, we report on the magnetotransport measurements in mono- and bi-layer graphene in pulsed magnetic fields up to $B = 53$ T. In a mono-layer graphene, the Hall resistance is quantized into $R_{H} = \left(\frac{h}{e^2}\right) \nu^{-1}$ with integer values $\nu = \pm 2, \pm 6, \text{ and } \pm 10$ for either hole or electron doping, indicating the observation of half-integer QHE. In a bi-layer graphene, the $R_{H}$ is quantized to $R_{H} = \left(\frac{h}{e^2}\right) \nu^{-1}$ with $\nu = \pm 4, \pm 8, \text{ and } \pm 12$. This is the observation of the integer QHE of massive chiral fermions in the bi-layer graphene. The measurement technique,
Figure 1. The optical images of (a) the mono-layer and (c) the bi-layer graphene. The outlines of the graphene flakes are highlighted by the dashed lines. The resistivity $\rho$ of the (b) mono-layer and (d) bi-layer graphene as a function of the $V_g$ at $T = 4.2$ K. (e) The magnetic field $B$ generated by the pulse magnet. (f) Time evolution of the Hall resistance $R_H$ of the mono-layer graphene with $V_g = 30$ V at $T = 4.2$ K.

established in this work, can be used effectively for the studies of QHE in mono- and bi-layer graphene in high magnetic fields.

2. Experiment

Mono-layer and bi-layer graphene flakes used in this study were extracted from Kish graphite and deposited onto a 300-nm-thick SiO$_2$ layer on top of heavily doped Si wafer using the conventional mechanical exfoliation technique of graphite. A large graphene flakes were selected using an optical microscope and the multiple electrodes were fabricated using electron-beam lithography (Elionix ELS 7500), followed by electron-beam evaporation of Au/Ti (40 nm /4 nm) [Fig. 1(a)]. The charge density $n$ of the graphene flake was tuned by applying a gate bias voltage $V_g$ to the heavily doped silicon wafer, which serves as global back gate [13, 14]. In order to remove the surface impurities, the devices were annealed in a measurement cryostat at $T \sim 400$ K in vacuum ($P \sim 1 \times 10^{-2}$ Pa) for several hours. Fig. 1 shows the resistivity $\rho$ of the (b) mono-layer and (d) bi-layer graphene as a function of the $V_g$. The $\rho$ shows a peak at (b) $V_g = 5$ V and (d) $V_g = -12$ V, indicating the charge neutrality points $V_{\text{Dirac}}$. The electron mobility of the mono-layer and bi-layer graphene are (b) $\mu = 4000$ cm$^2$/Vs and (d) $\mu = 3000$ cm$^2$/Vs at $V_g = 32$ V, respectively.

The magnetic field was generated by a pulse magnet immersed in liquid nitrogen. The magnet was energized by the 1 MJ capacitor bank. The value of the magnetic field was obtained by integrating the emf signal from a pick-up coil [Fig. 1(e)]. During the pulse, the voltage signals $V_{xy}$ were recorded with DC currents of $I = \pm 200$ nA. The voltage signals were subtracted each other to eliminate the field-induced background voltage. The $R_H$ was obtained by dividing the voltage signal by the current $I$ [Fig. 1(f)]. The trace of $R_H$ vs. $B$ was studied in a downward sweep because the magnetic field changes more slowly. Here, we emphasize the technical difficulties in measuring the QHE under the pulsed magnetic fields. When a pulsed magnetic field is applied, an additional transient current is induced in the sample and measurement circuits. This transient current results in the deformation of quantum Hall plateaus as observed in the conventional semiconductor two-dimensional electron gas systems. To obtain the well-developed Hall plateaus, Burgt et al. numerically compensated for the transient current flow in the device.
by assuming the appropriate capacitance [1]. Kido et al. used an active shielding technique; the voltages of the outer and inner conductors of the coaxial cables were equalized using the buffer amplifiers of unity gain thereby eliminating the capacitance of the circuits [15]. In both cases the reduction of the capacitance was a key for suppressing the deformation of quantum Hall plateaus. In our study, we employed copper wires inside the measurement cryostat thus reducing the capacitance of the circuit as less as possible, and all the other electric cables and measurement equipment including a computer were installed in a shield box set near the magnet to get rid of the electronic noise. This method has given sufficient high signal-to-noise ratio and suppressed the deformation effects.

3. Results and discussion
Figure 2 shows the $R_H$ as a function of the inverse of the magnetic field $B^{-1}$ measured in (a) mono- and (b) bi-layer graphene for gate-bias voltages (a) $V_g = 17.5$ and (b) -60 V at $T = 4.2$ K. In these measurements, the magnetic field was swept from $B = 53$ T to 0 T. In the mono-layer graphene, the Hall plateaus are visible at $R_H = 13.3$, $4.1$, and $2.2$ kΩ [dashed lines in Fig. 2 (a)], and these values correspond to the quantum Hall resistances of $R_H = \frac{h}{2e^2}$, $\frac{h}{6e^2}$, and $\frac{h}{10e^2}$ within 10% accuracy. In the bi-layer graphene, the Hall plateaus are observed at $R_H = 6.7$, $3.1$, and $2.2$ kΩ [dashed lines in Fig. 2 (b)], and these values correspond to the quantum Hall resistances of $R_H = -\frac{h}{4e^2}$, $-\frac{h}{8e^2}$, and $-\frac{h}{12e^2}$, respectively. This observation indicates the integer QHE of the massive chiral fermions in the bi-layer graphene in pulsed high magnetic fields. Here we emphasize that this is the first experimental observation of the integer QHE in the bi-layer graphene in pulsed high magnetic fields.

Next, we study the $R_H$ vs. $B$ up to 53 T at the various gate bias voltages. Fig. 3 shows the $R_H$ vs. $B$ measured for the mono-layer graphene at (a) $V_g = 17.5$ V, (b) 30.0 V, (c) 40.0 V, and (d) 48.0 V. The carrier densities in these conditions are calculated by using the standard formula for the graphene on SiO$_2$ layer: $n = \alpha (V_g - V_{Dirac})$ with the constant $\alpha = 7.2 \times 10^{10}$ cm$^{-2}$V$^{-1}$, as (a) $n = 9.0 \times 10^{11}$, (b) $1.8 \times 10^{12}$, (c) $2.5 \times 10^{12}$, and (d) $3.1 \times 10^{12}$ cm$^{-2}$, respectively. The filling factor $\nu$ is proportional to the carrier density and the inverse of the magnetic field $\nu = n\phi_0B^{-1}$, where $\phi_0 = 4.14 \times 10^{-15}$ Tm$^2$ is the flux quantum. By using this relation we calculated the expected positions of the quantum Hall plateaus for the filling factors $\nu = 2$, 6, and 10 as indicated by the red, green, and black arrows in Fig. 3, respectively. The Hall plateaus are
located exactly at the expected positions of the filling factors \( \nu = 2, 6, \) and 10. In the bi-layer graphene, the \( R_H \) vs. \( B \) was measured at (e) \( V_g = -26.0 \) V, (f) -40.0 V, (g) -50.0 V, and (h) -60.0 V. The carrier densities are calculated to be (e) \( n = 1.0 \times 10^{12} \), (f) \( 2.0 \times 10^{12} \), (g) \( 2.7 \times 10^{12} \), and (h) \( 3.4 \times 10^{12} \) cm\(^{-2}\), and the expected positions of the Hall plateaus at filling factors \( \nu = 4, 8, \) and 12 are indicated by the blue, purple, and grey arrows in Fig. 3, respectively. The plateaus in the \( R_H \) are located at the expected positions of the filling factors \( \nu = 4, 8, \) and 12. These results show that the QHE in mono-layer and bi-layer graphene are correctly measured for the various gate bias voltages in our experiments.

4. Summary

We have observed the integer QHEs in mono-layer and bi-layer graphene devices in magnetic fields up to \( B = 53 \) T by use of a pulse magnet. In a mono-layer graphene, Hall resistance \( R_H \) is quantized into \( R_H = (h/\epsilon^2)\nu^{-1} \) with filling factors \( \nu = \pm 2, \pm 6, \) and \( \pm 10 \). In a bi-layer graphene, the \( R_H \) is quantized to \( R_H = (h/\epsilon^2)\nu^{-1} \) with \( \nu = 4, 8, \) and 12. We have shown that precise magnetotransport measurements of the graphene can be conducted in the environment of pulse magnetic fields. This work is a step forward to a new possibility for investigating electrical properties of graphene in ultrahigh magnetic fields \( B > 100 \) T.
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