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Electron Focusing Effect in Ballistic Graphene Cross Junction

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1. Introduction

The unique band structure of monolayer graphene has lead to the emergence of relativistic charge carriers; massless Dirac fermions. Since the motion of Dirac fermions are governed by the relativistic transport formula, ballistic graphene devices exhibit exotic transport properties such as Klein-tunneling, evanescent-wave transport, and anomalous magnetic commensurability effects. For understandings of transport properties of massless Dirac fermions, elaborated investigations on the electron motion in ballistic graphene devices are demanded.

Recent developments in device fabrication technique have realized high-mobility substrate-supported graphene on hexagonal boron nitride (h-BN). Graphene on top of hexagonal boron nitride (h-BN) exhibit extremely high mobility $\mu \sim$ 100,000 $cm^2V^{-1}s^{-1}$. In such high-mobility graphene, the mean free path of charge carriers reaches on the order of microns, which is comparable to the sample size, and charge carriers travel ballistically. Therefore, graphene on hexagonal boron nitride is an ideal platform for studying the ballistic transport properties of massless Dirac fermions in graphene.

In this work, we report on magnetotransport measurements in ballistic graphene four-terminal square structures on hexagonal boron nitride. The value of Hall resistance R_H shows anomalous plateau-like structures at magnetic fields, where the cyclotron diameter $2R_c$ equals the size of square structure $\sim L$, indicating the observation of magnetic focusing effect of ballistic charge carriers from source to voltage probes. From the analysis on the charge carrier density dependence of R_H curves, the direct estimation of R_c of Dirac fermions can be made.

2. Experimental

The graphene/hexagonal boron nitride (GBN) was fabricated using the mechanical transfer technique of monolayer graphene on arbitral substrates [1]. Monolayer thickness of graphene layer was verified by Raman spectroscopy and atomic force microscopy measurements. Cross-shaped geometry was defined using the standard electron-beam lithography and subsequent oxygen plasma etching technique [Fig. 1]. The side length of cross-junction was L = 2 μm, and the width of terminal wire at each corner was W = 400 nm [Fig. 1]. Metal contacts were fabricated by electron-beam lithography, evaporation of Pd (80 nm) and lift-off. Finally, the resist residues were removed by annealing in Ar/H_2 (97:3) gas flow for 5 h.

Transport measurements were conducted using the standard digital lock-in technique in a variable temperature insert. Hall resistance R_H was measured by applying a small alternating current of I_{ac} = 100 nA between terminal 1 and 3, and measuring voltage between terminals 2 and 4. Magnetic field B was applied perpendicularly to the sample surface using superconducting magnet. A conducting Si substrate was used as a global back gate to tune charge carrier density as $n = C_g(V_g - V_{Dirac})$ where $C_g = 1.07\times10^{-4}$ F/m^2 is the gate-capacitance and V_{Dirac} is the value of V_g at charge neutrality point.

3. Results and Discussions

The top curve in Fig. 2 shows Hall resistance characteristics measured at T = 10 K for V_g = -32 V in the device shown in Fig. 1. As the magnetic field was increased from zero, R_H increased linearly with B. For larger B, R_H deviated from the classical linear value at B = 0.06 T and made a plateau structure at $B \sim$ 0.18 T. As B was further increased, the value of R_H converged again to the classical linear value

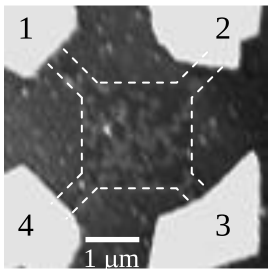

Fig. 1. AFM image of the device studied in this work. The characters S, D, and V indicate Source, Drain, and Voltage probes, respectively.

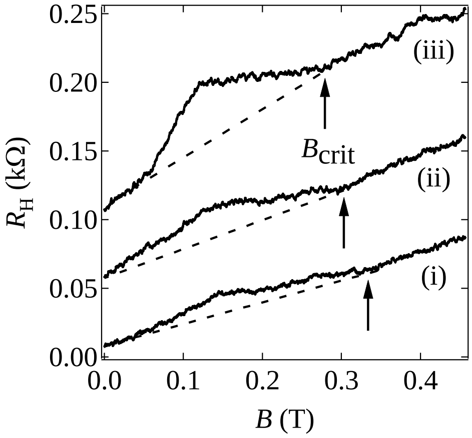

Fig. 2: Hall resistance R_H as a function of magnetic field B for various back-gate voltage V_{BG} at temperature T = 10 K. Back-gate bias voltage was V_{BG} = (i) -50 V, (ii) -41 V, and (iii) -32 V, respectively (Dirac point is located at V_{BG} = -0.6 V). The R_H curves are offset vertically by 0.05 kΩ for clarity.

at B = 0.3 T. The deviation of R_H from the classical value and subsequent conversion was consistent with the case of previous magnetotransport measurements in conventional ballistic two-dimensional electron system. Thus, the observed deviation of R_H can be attributed to ballistic transport of charge carriers from source to voltage probes by the cyclotron motion as schematically shown by the white arrow in Fig. 1.

When the value for charge carrier density n was decreased, the positions of plateaus $B_{plateau}$ was decreased as shown in Fig. 2 (i)-(iii). This observation can be explained by the dependence of cyclotron radius R_c on n. From the analysis on the magnetoresistance curve dependence on n, the estimation for cyclotron radius R_c of Dirac fermions can be made. The discussions on this point will be given in the presentation.

4. Conclusion

We studied magnetotransport properties of ballistic graphene four-terminal square structures, where the charge carrier mean free path is comparable to the sample size. The Hall resistance R_H exhibited plateau-like structure in magnetic fields where the cyclotron radius is comparable to the junction size, which demonstrates the observation of electron focusing effect in graphene junction. From the analysis on the charge carrier density dependence of R_H curves, the direct estimation of R_c of Dirac fermions can be made. These observations are fundamental step forward for understanding transport dynamics of massless Dirac fermions in graphene.

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