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Quantum Interference in a Ballistic Graphene *n-p-n* Junction: Fabry-Perot Interference and a Novel Magnetoresistance Oscillation

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Abstract

We observed two types of magnetoresistance oscillations in a ballistic graphene *n-p-n* junction. The low-field resistance oscillation is attributed to the Fabry-Perot interference in the graphene *n-p-n* cavity. The high-field oscillation is a novel magnetoresistance oscillation, which we interpret as a consequence of the flux quantization in an insulating strip between co-propagating quantum-Hall edge channels. These interference phenomena were clearly observed owing to the extremely high carrier mobility in graphene encapsulated with h-BN fabricated with the mechanical exfoliation and dry transfer of atomic layers.

1. Introduction

A graphene *p-n* junction is a promising platform for investigating peculiar transport phenomena of Dirac fermions such as Klein tunneling and anomalous electronic-wave refraction with a negative refraction index. In order to observe these phenomena, we need high-quality graphene *p-n* junctions in which the charge carriers travel ballistically. In a conventional graphene *p-n* junction, however, the interaction between graphene and a dielectric material degrades the charge carrier mobility.

In this work, we used hexagonal boron nitride (h-BN) as a dielectric layer in order to eliminate degradation of the carrier mobility due to extrinsic scattering sources. In low magnetic fields, we observed the Fabry-Perot interference, indicating that the charge carriers travel ballistically and coherently in the *n-p-n* cavity. We also observed a novel magnetoresistance oscillation in high magnetic fields. The peak and dip positions of the resistance oscillation are reproduced by a numerical simulation based on a new commensurability between the magnetic flux enclosed within the co-propagating quantum Hall edge channels and the magnetic flux quantum.

2. Graphene *n-p-n* junction

We fabricated a dual-gated graphene device [Fig. 1(a)] by mechanical exfoliation and dry transfer techniques. First, h-BN flake (~30 nm) was deposited on a Si wafer covered with 290 nm-thick thermally grown SiO_2. The heavy doped Si substrate can be used as a global back gate. Then, a monolayer graphene and another h-BN flake were placed on h-BN using a dry transfer procedure. Finally, source-drain contacts and a top gate electrode are defined by standard electron-beam lithography process. The width W and length L of the top-gated region are 1700 nm and 430 nm, respectively.

The *n-p-n* junction with tunable doping levels (n_b-n_t-n_b, respectively) was formed in graphene by applying the back and top gate-bias voltages [Fig. 1(a)]. The carrier mobility exceeds 100,000 cm^2/Vs at T = 1.6 K., which was realized because the surface of h-BN is atomically flat and h-BN has a high optical phonon energy compared to conventional dielectrics such as SiO_2 [1].

3. Fabry-Perot Interference

Fig. 1(b) shows two-terminal resistance R at T = 1.6 K. as a function of n_t at $n_b = -1.5 \times 10^{12}$ cm^{-2}. We observed a distinct oscillation which is attributed to the Fabry-Perot interference of charge carriers in the *n-p-n* cavity [Fig. 1(c)]. Furthermore, when a small magnetic field was applied perpendicular to graphene, the oscillation phase was shifted by π [Fig. 1(d)], indicating the observation of Klein Tunneling [2], which is an intrinsic phenomenon of Dirac Fermion.

These observations indicate that the charge carriers travelled ballistically and coherently over the macroscopic cavity length of L = 430 nm, demonstrating the markedly high quality of our *n-p-n* junction. In previous experiments using graphene on SiO_2, the observation of the Fabry-Perot interference required very small cavity length of L = 20 nm, because the charge carrier mean free path was limited [2]. These results suggest graphene/h-BN heterostructures provide a new suitable platform for investigating novel charge carrier transports in graphene *p-n* junctions.

4. Novel Magnetoresistance Oscillations

Next, we study the transport properties of our high mobility *n-p-n* junction in high magnetic fields up to B = 9 T. The left panel of Fig. 2(a) shows a color plot of R as a function of n_t and B at $n_b = -2.2 \times 10^{12}$ cm^{-2}. Aperiodic resistance oscillations emerge as a function of B at B > 2 T. The anomalous interference patterns have not been reported in earlier magnetotransport measurements in low mobility *n-p-n* junctions [3].

The line cuts of the data for n_b = -1.7, 1.1, 0.5 $\times 10^{12}$ cm^{-2} (top to bottom) were shown in Fig. 2(b). The novel resistance oscillations appear only in an intermediate magnetic field range. When *B* was increased from zero, *R* was increased and started to oscillate as a function of *B*. When *B* was increased further, the oscillation amplitude was gradually diminished. In Fig. 2(c), we plot the oscillation period ΔB, derived from Fig. 2(b). When *B* was increased, ΔB was gradually decreased. Such dependence of ΔB on *B* depicts the peculiar aspect of the oscillations because the dependence misfits those expected for the conventional effects such as Shubnikov-de Haas oscillation ($\Delta B \propto B$) or Aharanov-Bohm effect in the top-gated region (ΔB = Const.).

The numerical simulation based on the flux quantization in the insulating strip at the *p-n* junction can reproduce the peak and dip positions as described below. We considered the magnetic flux Φ penetrating through the insulating region enclosed between the co-propagating quantum Hall edge channels [Fig. 2(d)]. By using $N = \Phi/\phi_0$ (ϕ_0 is a flux quantum), we calculated the positions where *N* takes an integer value such as *N* = 1, 2, …, 20 [The right panel of Fig. 2(a)]. For different experimental parameters, we also observed the resistance oscillations and, again, the calculations were well fitted to the experiments [Fig. 2(e, f)].

These results and calculations suggest the presence of a new transport mechanism at the *p-n* junctions in high magnetic fields. It can be scaled by the number of magnetic flux between quantum Hall edge channels at *p-n* junctions, as if the interference between edge channels occured. We observed such a peculiar phenomenon for the first time, probably because the scattering between edge channels was strongly suppressed in our high mobility *n-p-n* junction.

5. Conclusions

We studied transport properties of a ballistic graphene *n-p-n* junction. The graphene was sandwiched between two h-BN crystals in order to eliminate the mobility degradation. We observed the Fabry-Perot interference in low magnetic fields and the novel magnetoresistance oscillations in high magnetic fields. These results indicate that h-BN is an ideal dielectric material for investigating the physics of graphene and we can find the presence of a new mechanism of quantum Hall transport in a graphene *p-n* junction, thanks to its high quality.

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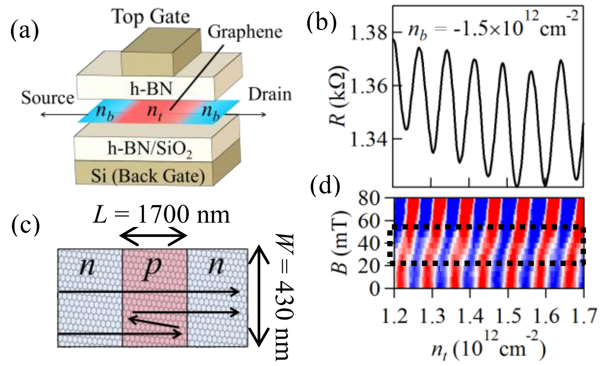

Fig. 1: (a) The schematic of our dual-gated device. (b) The oscillation of *R* attributed to the Fabry-Perot interference. (c) The schematic of the interference. (d) The phase shift of the oscillation of dR/dn_t induced by Klein Tunneling

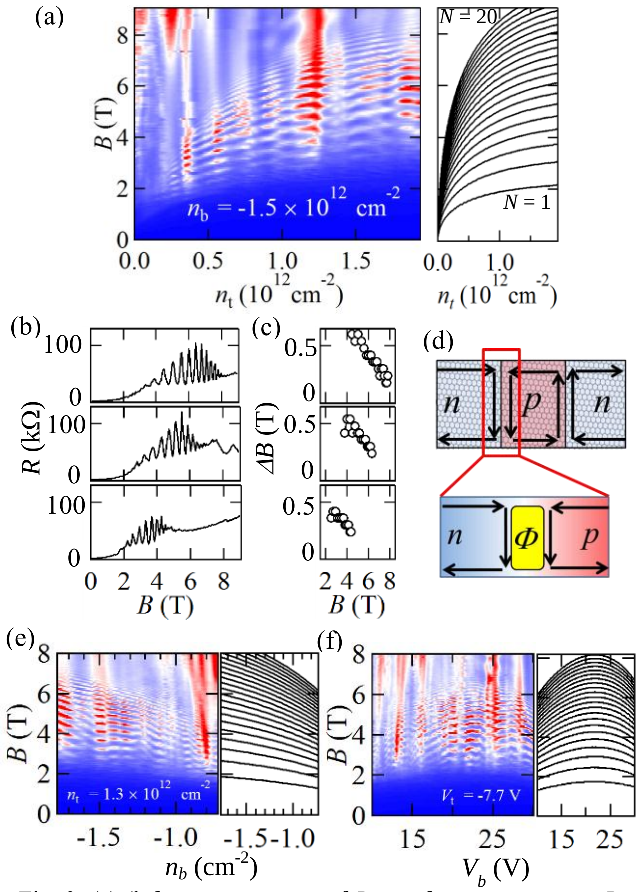

Fig. 2: (a) (left) The color plot of *R* as a function of n_t and *B*. (right) The calculated positions where *N* = 1, 2, …, 20 (bottom to top). (b) The line cuts of (a). (c) The oscillation period ΔB as a function of *B*. (d) The magnetic flux Φ penetrating through an insulating strip enclosed between the co-propagating quantum Hall edge channels at the *p-n* interface. (e, f) The comparison between experiments and calculations for experimental parameters different from (a).