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 ($n_p$, $n_d$) 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 $n_p$ at $n_d = -1.5 \times 10^{12}$ 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 $\pi$ [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 $n_p$ and $B$ at $n_d = -2.2 \times 10^{12}$ 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 \( n_s = -1.7, 1.1, 0.5 \times 10^{12} \) 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 \( \Delta B \), derived from Fig. 2(b). When \( B \) was increased, \( \Delta B \) was gradually decreased. Such dependence of \( \Delta B \) 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 Aharonov-Bohm effect in the top-gated region (\( \Delta B = \text{ Const.} \)).

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 \( \Phi \) penetrating through the insulating region enclosed between the co-propagating quantum Hall edge channels [Fig. 2(d)]. By using \( N = \Phi / \Phi_0 \) (\( \Phi_0 \) is a flux quantum), we calculated the positions where \( N \) takes an integer value such as \( N = 1, 2, \ldots, 20 \) [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 occurred. 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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References


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 \( dR/dn \) induced by Klein Tunneling.

Fig. 2: (a) (left) the color plot of \( R \) as a function of \( n_s \) and \( B \). (right) The calculated positions where \( N = 1, 2, \ldots, 20 \) (bottom to top). (b) The line cuts of (a). (c) The oscillation period \( \Delta B \) as a function of \( B \). (d) The magnetic flux \( \Phi \) 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).