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Dirac fermion reflector by ballistic graphene sawtooth-shaped npn junctions

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Abstract

We have realized a Dirac fermion reflector in graphene by controlling the ballistic carrier trajectory in a sawtooth-shaped npn junction. When the carrier density in the inner p-region is much larger than that in the outer n-regions, the first straight np interface works as a collimator, and the collimated ballistic carriers can be totally reflected at the second zigzag pn interface. We observed clear resistance enhancement around the npn regime, which is in good agreement with the numerical simulation. Though the effect observed is mild and needs more validation for future application with better device design, the qualitative tunable reflectance of ballistic carriers could be an elementary and important step for realizing ultrahigh-mobility graphene field effect transistors utilizing Dirac fermion optics in the near future. We also comment on some possible guidelines to improve the quantitative device performance.

Keywords: graphene, ballistic transport, pn junction, field effect transistor, Dirac fermion optics

(Some figures may appear in colour only in the online journal)

1. Introduction

The development of fabrication methods for high-mobility graphene/h-BN [1–5] has recently unveiled ballistic carrier-transport phenomena in graphene such as negative bend resistance [4, 6], the magnetic focusing effect [7–9], and a magnetoresistance peak due to boundary scattering [10]. Under such a ballistic carrier transport regime, the transmission of carriers can be described by an analogy to the geometrical optics of light, opening up a research field of ‘Dirac fermion optics’ [11]. Indeed, by using reflection and refraction of ballistic Dirac fermions at an interface of different carrier-density regions, especially at a pn interface, numerous characteristic functionalities have been realized experimentally, such as waveguides [12], Veselago lenses [13], beam splitters [14], and edge-channel interferometers [15]. More recently, systematic experimental studies on Snell’s law at ballistic graphene pn junctions were reported [16]. In these systems, the pn interface can be utilized as an optical component between different refractive-index regions, e.g., lens, mirror, or prism.

Ballistic carrier transport has also been proposed as a tool to turn currents ON and OFF in graphene without inducing an energy gap by using tilted pn junctions [17–22]. First, some groups proposed the graphene electro-optic transistor by a single tilted junction [17–19], and then Sajjad et al proposed a more efficient way by combining the collimation and total reflection of ballistic carriers using two sequential pn junctions (npn junctions) with different tilted angles for suppressing ballistic carrier transmission in graphene [20]. After that, Wilmart et al analyzed a more detailed performance of the tilted npn junctions with high-bias characteristics by the non-equilibrium Green’s function (NEGF) method [22]. This method has advantages for microwave electronics because the OFF state can be realized at a high-carrier-density region without degrading the graphene’s carrier mobility by using Dirac fermion optics, which is totally different from conventional methods such as the creation of
nanoribbons [23], addition of embedding defects [24], and use of bilayer graphene [25, 26].

In this paper, we experimentally demonstrate resistance enhancement in sawtooth-shaped npn junctions by using the collimation and total reflection of ballistic carriers. The tunable reflectance of ballistic carriers is a key ingredient of field effect transistors (FETs) that has been proposed [17–20, 22] and it could be an elementary and important step for realizing ultrahigh-mobility graphene FETs utilizing Dirac fermion optics. Since the effect observed is quantitatively small at this stage, we need finer-tuning for better device design, which will also be commented on in the latter part of section 4.

2. Theory and methodology

First, we consider an interface between two regions of graphene with different carrier densities \( n_1 \) and \( n_2 \) (figure 1(a)). The flow of ballistic carriers in the two regions can be regarded as the propagation of electron waves whose wave vectors are \( |n_1| \overline{\pi}^{0.5} \) and \( |n_2| \overline{\pi}^{0.5} \), respectively. Analogous to light in the geometrical optics regime, the incident ballistic carrier wave is refracted according to Snell’s law [27],

\[
\sin \theta_2 = \frac{1}{n_2} \sin \theta_1
\]

The refraction angle \( |\theta_2| \) is smaller (larger) than the incident angle \( |\theta_1| \) when \( |n_1| > |n_2| \) \((|n_1| > |n_2|)\). Even negative refraction can occur if \( n_1 n_2 < 0 \) [27].

Next, we consider a graphene in-plane junction whose carrier densities are \( n_1 \), \( n_2 \), and \( n_1 \), respectively, as shown in figures 1(b) and (c); the right interface is tilted from the left interface by an angle of \( \alpha \). When \( |n_2| > |n_1| \) is satisfied, the flow of ballistic carriers injected to the first straight interface (left interface in figures 1(b) and (c)) from an unrestricted incident angle is collimated to a limited refraction angle between \( -\theta_c \) and \( \theta_c \) after the transmission through the interface, where the critical angle \( \theta_c \) is given by \( \theta_c = \frac{\pi}{2} |\theta_1| \). The first interface can be regarded as a collimator for the electron wave in graphene. Then, the electron wave collimated within the spread angle \( 2\theta_c \) is transmitted to the second interface (right interface in figures 1(b) and (c)) with an incident angle between \( -\theta_c + \alpha \) and \( \theta_c + \alpha \). If all the incident angles are larger than \( \theta_c \), i.e., \( 2\theta_c \), all the incident ballistic carriers are totally reflected at the second interface. This condition can be realized when \( |n_2| > |n_1| \) is much larger than \( |n_1| \) because \( \theta_c = \arcsin(|n_1|/|n_2|)^{0.5} \). In this case, the transmission of ballistic carriers is completely suppressed; thus, the situation can be regarded as an OFF state in the FET operation. In addition, since the critical angle \( \theta_c \) can be controlled experimentally by changing the ratio of carrier densities.

Figure 1. (a) The refraction of ballistic carriers across the junction between different carrier density regions. (b) and (c) The schematics of the mechanism of transmission manipulation in triangular junctions, corresponding to the OFF state (b) and ON state (c). (d) \( T(\phi) \) of smooth \((d = 120 \text{ nm, solid}) \) and abrupt \((d = 1 \text{ nm, dotted}) \) pn junctions. (e) \( T(\phi) \) of smooth \((d = 120 \text{ nm}) \) pn (solid) and nn (dotted) junctions. Both (d) and (e) are derived using equation (10) in Cayssol et al [31], and blue (red) curves correspond to the instance when the carrier transmits through the interface from lightly doped (heavily doped) to heavily doped (lightly doped) regions. The absolute value of lightly (heavily) doped carrier density is 0.9 × 10^{13} \text{ cm}^{-2} (2.0 × 10^{12} \text{ cm}^{-2}). (f) Simulation result of the resistance as a function of \( n_2 \) and \( n_1 \) across the triangular-shaped carrier-density-modulated region, which is depicted in the inset.
densities in the two regions according to $\theta_c = \arcsin(|n_1|/n_2)$, we can switch between the OFF state (figure 1(b)) and the ON state (figure 1(c)) electrostatically. The advantage of this concept for microwave electronics is that we can realize the OFF state even by increasing the carrier density $|n_2|$. This implies that we can use this device while keeping the regime with large carrier density, which benefit the dynamical and noise properties of the device due to the large intrinsic transmission [17]. Such a concept is totally different from the normal method realizing the OFF state around the zero carrier density region, which is around the Dirac point in the case of graphene.

We also extend our model to include the effect of the split junction in a realistic device, considering an angle distribution of transmission probability across the junction $T(\phi)$ [17, 28–30], which can be derived from equation (10) in Cayssol et al [31]. $\phi$ is the incident angle of ballistic carriers to the junction. In particular, when the potential profile across the junction is smooth owing to the finite thickness of the top gate dielectric, $T(\phi)$ is much sharper than in an abrupt junction with a strong angular filtering similar to the Gaussian one, as shown in figure 1(d). Moreover, as shown in figure 1(e), $T(\phi)$ in a pn junction is significantly suppressed except at $\phi \sim 0$ even if $\phi < \theta_c$, compared to that in an nn junction. Such results indicate that in smooth npn junctions with a sawtooth-shaped gate, the collimation effect at the first interface and the filtering effect at the second interface become more prominent, and the OFF current can be suppressed more than that in sharp and/or nn junctions, although the ON current is also suppressed [20, 22].

By using such $T(\phi)$, we used the scattering theory as in Wilmart et al [22], rather than the NEGF method, because NEGF requires too much computational resource: we numerically calculated the resistance across one simple triangular-shaped ballistic region with a carrier density $n_2$ surrounded by a region with a carrier density $n_1$, as shown in the inset of figure 1(f). The larger the number of reflections we considered, the more the beam intensity inside the junctions decreases [22]. Therefore, in order to truncate the residual electrons inside the junction reasonably, we considered ten internal reflections of ballistic carriers in the triangular region, which is a sufficient number since we have checked that this truncation does not affect the reflection data by more than 10%. Following the experimental parameters from our devices examined below, we set the tilt angle $\alpha$ to $20^\circ$ and the length of the junction $d$ to correspond to a parameter of the steepness of the carrier density gradient, 120 nm, which was derived numerically using the finite element method. Figure 1(f) shows the result of resistance as a function of $n_1$ and $n_2$. In addition to the charge neutrality points, $n_1 = 0$ and $n_2 = 0$, we can see the resistance enhancement at the np$^+$n, pn$^+$p, np$^+$n, and pp$^+$p regions ($|n_2| \gg |n_1|$), which is consistent with our prediction that the reflection of ballistic carriers can be enhanced when $|n_2|$ is much larger than $|n_1|$. Note that the resistance enhancement for the bipolar regime is larger than that for the unipolar regime, which is consistent with the transmission probability difference shown in figure 1(e).

3. Device fabrication and characterization

In order to realize this ballistic device experimentally, we fabricated high-mobility dual-gated graphene by encapsulating graphene with h-BN crystals [32, 33] using the `'pick-up` transfer method [1]. First, we assembled h-BN/graphene/h-BN van der Waals heterostructures and attached Cr/Pd/Au one-dimensional contacts [1], following the same procedure used in our previous report, from which we can estimate that the expected carrier mobility is greater than 50 000 cm$^2$/Vs and the mean free path is of the order of 1 $\mu$m [8]. Then, we fabricated a metal top gate by using the top 50 nm-thick h-BN as a dielectric. The metal top gate is sawtooth-shaped, as shown schematically in figure 2(a). The sawtooth shape consists of a sequence of triangular junctions, and the elementary unit is a doped region depicted in figure 2(a), embodying our concept in figures 1(b) and (c), whose tilt angle $\alpha$ is $\sim 20^\circ$ with a variation of $\pm 5^\circ$ due to the lithography imperfection. The influence of this variation on the results will be discussed later. By using the sawtooth shape, i.e., the sequential triangular units, we kept the average local top-gate length $l$ sufficiently short ($<0.4 \mu$m) because we need to maintain the ballistic regime. An atomic force microscopy (AFM) image of this device is shown in the inset of figure 3(a). The channel width $W$ and length $L$ are ($W$, $L$) $\sim (2.4, 2.2) \mu$m. We used a conventional lock-in technique and measured the four-terminal resistance $R_{4t}$. By tuning the back-gate and top-gate bias voltages $V_b$ and $V_t$, we can independently control the carrier densities $n_2$ and $n_1$ of the top-gated region and the uncovered region through $n_2 = (C_V + C_b V_b)/e$ and $n_1 = (C'_V + C_b V_b)/e$, as depicted schematically in figure 2(b), where $C_b$ is the back-gate capacitance and $C_V$, $C'_V$ are top-gate capacitances for the regions with carrier density $n_2$, $n_1$, respectively. The values of $(C_b, C_V, C'_V) = (1.2, 6.0, 0.1) \times 10^{-4}$ C m$^{-2}$ can be derived from the quantum Hall measurements and the slope of the Dirac point trajectories in the $(V_b, V_t)$ plane [34]. We performed experiments at $T = 120$ K so that the carrier transport could be maintained in a ballistic regime and coherent resistance oscillations could be suppressed owing to the thermal phase averaging [13], i.e., an experimental
condition where the carrier mean free path $L_{\text{mfp}} > \text{average local top-gate length} l > \text{the thermal length} L_T$. We observed a negative resistance in $R_{\text{at}}$ for $n_2 = n_1$ at $T = 120$ K, as shown in figure 3(a), which is qualitatively the same as the earlier observation of the negative bend resistance [6] and can be regarded as a signature of the ballistic carrier transport regime.

4. Results and discussion

Figure 2(c) shows the experimental results for $R_{\text{at}}$ as a function of $n_2$ and $n_1$. In the vicinity of the np$n$ and pn$p$ regime ($|n_2| > |n_1|$ and $n_1, n_2 < 0$), $R_{\text{at}}$ clearly shows resistance enhancement, which qualitatively agrees well with our simulation result in figure 1(f). We cannot see clear resistance enhancement around the nn$n$ and pp$p$ regime ($|n_2| > |n_1|$ and $n_1, n_2 > 0$), possibly because the collimation and total reflection effect are so small in this regime, supported by the relatively broad transmission probability distribution in an nn junction as shown in figure 1(e), that they could be comparable to the other ballistic effects such as negative bend resistance [6].

Figure 3(a) shows $R_{\text{at}}$ as a function of $n_2$ at fixed $n_1 = 0.9$, 1.2, ..., 7.8 $\times$ 10$^{11}$ cm$^{-2}$ (top to bottom), corresponding to the line cuts of figure 2(c). For the np$n$ ($n_2 < 0$) regimes, $R_{\text{at}}$ is strongly enhanced when we increase $|n_2|$. In addition, the dip position of the $R_{\text{at}}$ versus $n_2$ curve, which corresponds to the place where the resistance enhancement starts (as indicated by a purple arrow), moves toward higher $|n_2|$ as we change $|n_1|$ to larger values. These results are qualitatively consistent with our proposal that the ratio of $|n_2|/|n_1|$ is important for resistance manipulation and should be large in order to realize the collimation and total reflection of ballistic carriers. The reproducibility of such resistance enhancement is also checked for another sawtooth-shaped np$n$ junction with $\alpha \sim 20^\circ$, as shown in figure 3(c). Even though the maximum carrier density is different from that in figure 3(a) owing to the different gate leak voltage, we kept the same length scale of the x-axis for the same carrier-density interval for fair comparison between figures 3(a) and (c). We can also see the resistance enhancement in figure 3(c), which support the qualitative reproducibility of the switching effect we discussed. Also, the enhancement for both devices have almost the same slope in $R_{\text{at}}$-np$n$ plots ($\sim$0.1 k\(\Omega\)/ 10$^{12}$ cm$^{-2}$ at $n_1 = 0.9$ $\times$ 1011 cm$^{-2}$) quantitatively, which should be validated with more sample statistics in the near future. The performance of this device, characterized by $\Delta R \sim 0.2$ k\(\Omega\) and $R_{\text{at}}$ as functions of $n_2$ at $n_1 = 0.9, 1.2, ..., 4.2$ $\times$ 10$^{11}$ cm$^{-2}$ (top to bottom). Though we cannot reach the high-$n_2$ region owing to the leakage problem, the signs of slopes around np$n$ regions, compared to figure 3(a), are the same in (c) and different in (d). AFM images of the measured devices are shown in the insets of (a), (c), and (d). The black dotted lines represent the edge of graphene, and the blue scale bar indicates a length of 500 nm. We measured $R_{\text{at}}$ by injecting current from $S$ to $D$ and measuring the voltage between $V_1$ and $V_2$. In the inset of (b), the device structure considered in the simulation is also shown.

To compare these experimental results with the simulated results, figure 3(b) shows line cuts of figure 1(f) for the same value of $n_1$ as in figure 3(a). The qualitative behaviors that we discussed above are all well reproduced. In addition, the approximate order of the value of resistance ($\sim$0.6 k\(\Omega\)) and the dip position trajectories with increasing $n_1$ (see appendix A) show good quantitative agreement without any fitting parameter, which indicates the predictive character of our simulation model and the high quality of our device.

To confirm that the resistance enhancement observed in the present work is due to the sawtooth gate junction, the same measurements were carried out in another device with a rectangular junction, as shown in the inset of figure 3(d). This device was fabricated from the same h-BN/graphene/h-BN flake and was measured at the same time as the device used in figure 3(c). In this device, we did not observe resistance enhancement (figure 3(d)) and such qualitative sign difference
of resistance slope as a function of \( n_2 \) between sawtooth and rectangular junctions confirms that the collimation and total reflection of ballistic carriers enhance the resistance in figures 3(a) and (c).

Our resistance enhancement, characterized by \( \Delta R \sim 0.2 \) kΩ and \( R_{\text{off}}/R_{\text{on}} \sim 1.3 \) from figure 3(a), is not sufficiently large at this stage and needs more modification of the device design. Actually, even between the bulk graphene and single pn junction one can induce the same order of ON/OFF ratio \((\gg 1.1 \text{ from } [20])\). However, the combination of collimation and total reflection using npn junctions could potentially induce more suppressed OFF current and even the transport gap \([20, 22]\), so we suggest three points to improve the performance of this device for future applications. First, we would eliminate the lithography roughness in the sawtooth gate shape and establish the influence of this roughness on the FET performance because geometrical imperfections could lead to spurious reflections or optical aberrations. Second, we would consider the influence of edge scattering and the dependence of FET performance on the tilt angle \( \alpha \). From the scattering theory without considering edge scattering \([22]\), \( \alpha \sim 45^\circ \) is the most appropriate angle for realizing large resistance enhancement. However, as shown in appendix B, we cannot observe any larger resistance enhancement in devices with \( \alpha \sim 45^\circ \). From other simulation results, including the effect of edge scattering, though the gate structure is a little bit different from our device, the transmission becomes even maximum at \( \alpha \sim 45^\circ \) \([29]\). Therefore, it is a future task for us to find the best value of \( \alpha \) from both theoretical and experimental studies using several devices with different \( \alpha \) in order to realize a much higher resistance enhancement. As another possible factor, we might have to consider the fact that the edge of the sample is not exactly perpendicular to the collimator (first junction), as can be seen in the inset of figure 3(a), which could change the influence of edge scattering. Finally, the profile of the local electrostatic potential at the junction should be modified depending on the purpose. As expected from the effect of potential steepness on the transmission probability shown in figure 1(d), the total transmission should change if we change the steepness of the junction potential. If the device requires a large gain, which implies a large ON current, the potential should be steep. On the other hand, if we need a suppressed OFF current, the potential should be smooth. By changing the thickness of the h-BN dielectric layer, which determines the steepness of electrostatic potential at the junction, we can tune such properties as required.

Since this device has the potential to realize an OFF state at a high carrier density region, it could be a breakthrough for the application of graphene FETs in microwave electronics \([22]\) without inducing mobility degradation. In addition, many graphene devices have recently been found to show ballistic effects even at room temperature \([6]\), and we actually observed resistance enhancement up to 280 K (see the temperature dependence and its correlation with the carrier mean free path in appendix C). Such temperature robustness results from the graphene’s high mobility at room temperature due to high optical phonon energy, which is the advantage of graphene over the other semiconductor materials for future applications.

5. Summary

In summary, we electrostatically realized a Dirac fermion reflector by using ballistic sawtooth-gate npn junctions. We compared our experimental results with simulations and established that the phenomenon is due to the collimation and reflection of ballistic carriers at pn interfaces. Though the effect observed is quantitatively mild and needs more validation for future application with better design as discussed in the latter part of section 4, our results qualitatively constitute a vital first step toward the realization of Dirac fermion optics for functional devices such as graphene transistors with ultrahigh mobility \([17–22]\).

Acknowledgments

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Appendix A. Dip position movement in \((n_1, n_2)\) plane

In order to check the quantitative agreement between the experiment and simulation, we plotted the dip positions of the results in figures 3(a) and (b) on the \((n_1, n_2)\) plane (figure A1). The black circles and red curves show the experimental and simulation dip positions, respectively.

![Figure A1](image-url)
Appendix B. Results from other devices with different tilt angle

We fabricated four devices with a tilt angle $\alpha \sim 45^\circ$, but we could not observe any resistance enhancement from any of them. For example, the results and device structure of one of the devices is shown in Figure B1. This is somehow inconsistent with Wilmart et al [22]. Nevertheless, we found that some other calculation results suggest that resistance enhancement across a tilted junction, which admittedly does not have the exact same shape as our junction, shows a transmission maximum around the tilt angle $\sim 45^\circ$, if the influence of edge scattering is considered [29]. Our next step would be to establish the best tilt angle while taking into account both our device structure and the effect of edge scattering.

Appendix C. Temperature dependence of resistance enhancement

Figure C1(a) shows the temperature dependence of resistance enhancement we observed. In order to quantify the result, figure C1(b) shows the temperature dependence of the resistance difference between np n and np' n regimes. Because of the temperature robustness of ballistic transport in graphene, the enhancement is sustained up to 280 K. The carrier mean free path $l_{\text{mfp}}$ of a device with similar quality from other reports [1] is also plotted in figure C1(c). At 280 K and 150 K (black vertical lines), when $\Delta R$ becomes zero and saturated to $\sim 0.15 \Omega$, respectively, $l_{\text{mfp}} / l$ is $\sim 2$ and $\sim 6$. These numbers are reasonable as one needs at least a roundtrip inside the sawtooth-shaped gated region to achieve total reflection.

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