Veselago focusing of anisotropic massless Dirac fermions

Shu-Hui Zhang and Wen Yang

1College of Science, Beijing University of Chemical Technology, Beijing, 100029, China and
2Beijing Computational Science Research Center, Beijing 100193, China

The massless Dirac fermions (MDF) emerge as the quasiparticles in various novel materials such as graphene and topological insulators, and exhibit a lot of intriguing properties in which the Veselago focusing is an outstanding example and has a lot of possible applications. However, the Veselago focusing merely occurs in the p-n junction based on the isotropic MDF, and lacks the tunability for the realistic applications. Here, motivated by the continuing emergence of Dirac materials, we investigate the propagation behaviors of anisotropic MDF in the p-n junction structure. By projecting the Hamiltonian of the anisotropic MDF to that of the isotropic MDF and deriving the exact analytical expression of the propagator, the precise Veselago focusing is demonstrated without demanding the mirror symmetry for an electron source and its focusing image, whose highly tunable features bring us to propose the device to probe the masked atom-scale defects. This study provides an innovative concept to realize the Veselago focusing and is relevant to its potential applications, and opens a venue to design the electron optics devices by exploiting the anisotropic MDF.

Introduction.—The massless Dirac fermions (MDF) emerge as the quasiparticles in a lot of novel materials, such as the well-known graphene and topological insulators. For the quasiparticles in the solid state environment, one prominent merit is the tunable energy dispersion by the proper experimental technique. Specific to graphene, its energy dispersion can be tuned by the strain, superlattice potential, and partially hydrogenated which change the MDF from isotropic to anisotropic. And the anisotropic MDF exist extensively in the other two-dimensional and three-dimensional Dirac materials. There is a continuing enthusiasm to exploit the unusual transport properties of MDF in various host systems, which are crucial to the future potential applications.

Due to the unique features of gapless and high mobility, the MDF are very ideal to realize the electron optics applications. The p-n junction (PNJ) based on the MDF as the basic element of device applications exhibits a lot of exotic electron optics phenomena in which the Veselago focusing is an outstanding example. The Veselago focusing implies that all electron waves diverging from a source across the junction converge into a focal image due to the negative refraction, lies in the heart of many theoretical proposals. In particular, the Veselago focusing has been observed in two recent experiments, which certainly boosts the relevant research interest. However, the PNJ based on the isotropic MDF is the only applicable system for Veselago focusing, and lacks the tunability for the realistic applications, e.g., the source is usually fixed which leads to the immovable focal image at its mirror position.

In this study, we study the propagation behaviors of anisotropic MDF in the PNJ structure. By projecting the Hamiltonian of the anisotropic MDF to that of the isotropic MDF, we derive the exact analytical expression of the propagator to show the precise Veselago focusing, which has superior tunable features. The tunable features not only lead to the novel design, e.g., to probe the masked defect by utilizing the tunable focusing position, but also favor the previous proposed applications based on the Veselago focusing. This study presents an innovative concept to realize the Veselago focusing beneficial to its potential applications, and provides a new way to design the electron optics devices by utilizing the anisotropic MDF.

Model and Hamiltonian.—The considered PNJ structure is shown schematically by the Fig. and it has the left N region and right P region. Each region of PNJ hosts the anisotropic MDF for which the anisotropic degrees can be different in the N and P regions. In general, the Hamiltonian of PNJ in Fig. has the form:

\[ \hat{H} = (\hat{H}_N + V_N)\Theta(-x) + (\hat{H}_P + V_P)\Theta(x), \]

where \( \hat{H}_i \) is the intrinsic Hamiltonian of \( i \) region with \( i \) adopting N or P. \( V_N = -V_0(\hat{V}_P = V_0) \) is the gate-induced scalar potential in N (P) region by assuming \( V_0 > 0 \) without loss of generality, and \( \Theta(x) \) is the step function: \( \Theta(x) = 1 \) for \( x > 0 \) and \( \Theta(x) = 0 \) for \( x < 0 \). In general, the anisotropic MDF of each uniform region can be described by using the Hamiltonian in which the MDF is \( i \) region. For the intrinsic Hamiltonian, it is easy to solve the eigenvalue problem, and the energy dispersion is \( \varepsilon_{\mu}(k) = \mu v_F \sqrt{k_{\perp}^2 + \Gamma^2_{\parallel}k_{\parallel}^2} \) where the index \( \mu = (\mu = -) \) is for the conductance (valence) band, \( k_\parallel = (k_{\perp}, k_\parallel) \) is the momentum vector, and the corresponding position vector is \( r = (x, y) \).

Green’s function and the projection method.—To investigate the propagation properties of anisotropic MDF in the PNJ structure, we concentrate on the corresponding the propagator or Green’s function (GF) which is defined as \( G(r_2, r_1, \varepsilon_F, V_0) = \langle r_2 | (\varepsilon_F + i \delta^+ - \hat{H})^{-1} | r_1 \rangle \) shown by the red line with an arrow in the Fig. Noting that \( G \) is a matrix due to the spinor nature of \( \hat{H} \). We have developed an simple and elegant method to derive the GF of isotropic MDF in graphene PNJ structure through the matching technique combining the translational invariance along the interface direction of junction. The generalization of this method to the anisotropic MDF is straightforward. However, here we present an alternative but more simple method, i.e., the projection method, which can give the PNJ GF of anisotropic MDF from that of isotropic MDF. To this aim, we
project the anisotropic Hamiltonian $\hat{H}_i$ into the form $\hat{H}_i^0 = v_F (\hat{\sigma}_x p_y + \hat{\sigma}_y p_x)$, where $\hat{H}_i^0 \equiv H_i / \Gamma_i$ is the Hamiltonian for the isotropic MDF, and $\hat{p}_i \equiv \hat{p}_x / \Gamma_i$. The corresponding energy dispersion is $\epsilon_k^0 (k^0) = \mu v_F \sqrt{(k_{i,x}^0)^2 + k_{i,y}^0}$ where $\epsilon_k^0 (k^0) = e_p (k^0) / \Gamma_i$ presents the projection relation for energy dispersion, $k^0 = (k_{i,x}^0, k_{i,y}^0)$ is the projected momentum vector with $k_{i,x}^0 = k_{i,y} / \Gamma_i$ and the corresponding position vector is $r^0 = (x^0, y^0)$ with $x^0 = \Gamma_i x$. Here, to obtain the projection relation $x^0 = \Gamma_i x$, we have used the constraint condition $\{\hat{x}, \hat{p}_x\} = [\hat{x}^0, \hat{p}_{i,x}^0] = i \hbar$ required by performing the Hamiltonian projection. Interestingly, the projection relation for energy dispersion changes the MDF from anisotropic to the isotropic as shown by Fig. 1(b). As a result, we obtain the equivalent PNJ of Fig. 1(a) but based on the isotropic MDF as shown by Fig. 1(c) through the projection relation for the position vector in real space, and the projection relation for the energy dispersion in the energy space leads to

$$\epsilon_k^0 = \frac{\epsilon_{r,i}}{\Gamma_i}.$$  (2)

Here, $\epsilon_r^0 = V_{N}^0 + e_p^0$ and $e_p^0 = V_F^0$ represent the doping levels since the Fermi level $e_i^0 (e_F^0)$ lie between junction potentials of N and P regions $\epsilon_r^0 \in [-V_{N}^0, V_{N}^0] (\epsilon_F^0 \in [-V_{P}^0, V_{P}^0])$ in the PNJ based on the isotropic (anisotropic) MDF. Obviously, the doping level defines the momentum through the energy dispersions, e.g., $\epsilon_r^0 (k^0) = v_F \sqrt{(k_{i,x}^0)^2 + k_{i,y}^0}$. In two equivalent PNJ structures, the GFs of the isotropic and anisotropic MDF are related to each other:

$$G(r_2, r_1, e_F, V_0) = G^0(r_2, r_1, e_F^0, V_0^0).$$  (3)

Here, the PNJ GF of the isotropic MDF [see the black line with an arrow in Fig. 1(c)] is defined as $G^0(r_2, r_1, e_F^0, V_0^0) = (r_2 | (e_F^0 + i0^+ - \hat{H}^0)^{-1} | r_1)$ where $\hat{H}^0$ is the PNJ Hamiltonian of the isotropic MDF in the form:

$$\hat{H}^0 = (\hat{H}_N^0 + V_{N}^0 I)\Theta(-\sigma) + (\hat{H}_P^0 + V_{P}^0 I)\Theta(\sigma).$$  (4)

**Analytical Green’s function of isotropic MDF.**—To be here, we need to derive PNJ GF of isotropic MDF. By examining the propagation phase and its derivative of higher order, we present the detailed analytical derivation of the PNJ GF of the isotropic MDF in the Supplementary Materials, which helps construct the intuitive physical picture for the propagation properties of isotropic MDF across the PNJ, i.e., the classical trajectories, negative refraction and then Veselago focusing. To assume a source at $r_1 = (-\alpha, 0)$, the Veselago focusing occurs at its mirror image $r_2 = \rho_{\text{IM}} = (\alpha, 0)$ and $e_p^0 = 0$ due to the requirement of a symmetric junction implying $\epsilon_{r,N}^0 = \epsilon_{r,P}^0$. The analytical formula for the PNJ GF of the isotropic MDF is $G^0 (\rho_{\text{IM}}, r_1, e_F, V_0^0) = G^0 (V_0^0)$ by using the definition

$$G^0 (V_0^0) = \frac{\rho(V_0^0)}{2\pi} \frac{\pi}{2 + 2\sigma_r}.$$  (5)

where $\rho(V_0^0) = V_0^0 / (2\pi v_F^2)$ is the density of states of the isotropic MDF with the doping level $V_0^0$. According to the primary cognition, on one hand, $G \propto V_0^0$ leads us to enhance the focusing intensity of the isotropic MDF by increasing the doping level through the electrical gating or other ways. On the other hand, the focusing position has no tunability and must be the mirror image of a fixing source, otherwise the intensity will decrease drastically. In fact, there is a hidden parameter dependence, $G \propto 1/v_F^2$, which clearly shows the enhancement of the focusing intensity by decreasing the Fermi velocity. If the Fermi velocity can be manipulated, this should be a more effective way than the control of doping level to enhance the focusing intensity since the GF has the complete dependent behaviors $G \propto V_0^0 / v_F^2$. Now, due to the rapid advance of the material science, a lot of Dirac materials have been discovered and have different Fermi velocities which really provide
various opportunities to electron optics, e.g., to enhance the focusing intensity. The general Dirac energy dispersion has two key variables, one is the Fermi velocity and the other one is the anisotropy. The manipulation of Fermi velocity is so promising in the electron optics that we are full of curiosity on the positive potential of the anisotropy as the subsequent topic.

**Tunable Veselago focusing by anisotropic MDF.**—Using the projection relations between the isotropic and anisotropic MDF, the propagation properties of anisotropic MDF across PNJ can be obtained conveniently (see Supplementary Materials). Here, we concentrate on Veselago focusing of anisotropic MDF and highlight its tunable features. The necessary conditions for the Veselago focusing of anisotropic MDF in PNJ can be given by using the projection relations:

\[
\begin{aligned}
& \mathbf{r}_2 = \frac{1}{\gamma} \mathbf{r}_1, \\
& \epsilon_r = \frac{1}{\gamma} \epsilon_0.
\end{aligned}
\]

Here, \( \mathbf{r}_1 = \mathbf{r}_0 \gamma / \Gamma_N = (-a \gamma / \Gamma_N, 0) \), the equation for \( \epsilon_r \) is due to Eq. 2 and \( \epsilon_0 = \epsilon_0 \gamma \) for the symmetric PNJ based isotropic MDF, and \( \gamma = \Gamma_P / \Gamma_N \) is the ratio of anisotropic degrees of P and N regions. In light of the anisotropic degrees, there are three cases: (1) If \( \gamma = 1 \) and \( \Gamma_N = \Gamma_P = 1 \), it recovers the case for the isotropic MDF, i.e., the Veselago focusing occurs for two sites with the mirror symmetry. (2) If \( \gamma = 1 \) and \( \Gamma_N = \Gamma_P \neq 1 \), it is for the anisotropic MDF. Comparing to case (1), the inter-site distance for Veselago focusing can be tuned by the anisotropic degree despite the mirror symmetry is still required. (3) If \( \gamma \neq 1 \), it is also for the anisotropic MDF. In this case, we can tune the focusing position for a fixing source and the Veselago focusing occurs in the asymmetric PNJ in contrast to the previous two cases. On the Veselago focusing of anisotropic MDF, we perform the numerical calculation to show the tunable focusing position by using \( \gamma = 2 \) and \( \gamma = 1 / 2 \) in Fig. (a) and (c) while Fig. (b) for the isotropic MDF (namely \( \gamma = 1 \) and \( \Gamma_N = \Gamma_P = 1 \)) is as a reference.

Furthermore, the intensity of Veselago focusing can also be tuned by changing the anisotropy of MDF. By using the projection relation, the PNJ GF based on the anisotropic MDF can be expressed as \( \mathcal{G}_{\gamma} = \mathcal{G}_{\gamma} / (\Gamma_N + \Gamma_P) \mathcal{G}_0 \) where \( \mathcal{G} \) given by Eq. 5 is GF of isotropic MDF with the doping level \( V_0 \) and the prefactor is introduced by anisotropy of MDF. Therefore, identical to the isotropic MDF, the focusing intensity of anisotropic MDF can be also enhanced by increasing \( V_0 \) and by decreasing the Fermi velocity \( v_F \). Besides, the ratio

\[
\mathcal{G}_r / \mathcal{G} = 2 / (\Gamma_N + \Gamma_P)
\]

shows the intensity modulation by the anisotropic degrees \( \Gamma_N \) and \( \Gamma_P \) of MDF in the N and P regions. The modulations of focusing intensity can be clearly seen in Fig. (d) which compares the Veselago focusing by considering different values of \( \gamma \), and the quantitative relations among the different intensities are fully described by the Eq. 7.

**Potential applications and discussions.**—In the ballistic regime, even a single scatterer may influence the whole device, the detailed understanding of the influence of such defects on electronic transport is necessary in order to exploit or avoid their influence. However, it is very difficult to identify the masked defects. As a novel application, we propose the device by utilizing the tunable focusing position of

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**FIG. 2.** Veselago focusing of anisotropic massless Dirac fermions shown by the magnitude of |\( G_{21} \)| as the function of \( r_2 = (x_2, y_2) \). Here, \( G_{21} \) is the matrix element of propagator matrix \( \mathbf{G}(r_2, r_1, \epsilon_r, V_0) \). No loss of generality, we assume \( r_1 = (-500, 0) \), \( V_0 = 0.2 \) and \( \Gamma_N = 1 \). (a) \( \epsilon_r = -V_0 / 3 \), and \( \Gamma_P = 2 \). (b) \( \epsilon_r = 0 \), and \( \Gamma_P = 1 \). (c) \( \epsilon_r = V_0 / 3 \), and \( \Gamma_P = 1 / 2 \). (d) \( |G_{21}| \) as the function of \( x_2 \) for \( y_2 = 0 \), in which three colored lines are obtained, respectively, from the corresponding dashed lines with the same color in (a), (b), and (c). In the plot, we define the unit length \( a \) and unit energy \( t_0 \) through \( v_F = 3 / 2a \) by analogy to graphene.
FIG. 3. The proposed device to probe the masked atom-scale defect in the Cartesian coordinate system \((e_x, e_y)\). Graphene is sandwiched between the top and bottom substrates which may contact to the gates\(^{2,33}\). By using the gates, one can form the PNJ which has the left N or encapsulated region with green color and the right P or unencapsulated region with blue color. By applying the superlattice potential or the strain on the substrate below the unencapsulated region, the anisotropic MDF is obtained in the P region with the tunable anisotropic degree \(\Gamma_P\). Assuming a defect denoted by the black dot at \(r_1 = (x_1, y_1)\) in the N region, combining the Veselago focusing and the anisotropic MDF of P region, the focusing image can occur at \(r_2 = (x_2, y_2) = (-x_1/\Gamma_P, y_1)\) (see Eq. 6 with \(\Gamma_P > 1\)) as the red circle or at \(r^*_2 = (x^*_2, y^*_2) = (x_1, y_1)\) (see Eq. 6 with \(\Gamma_P = 1\)) as the black circle. i.e., the realization of the probe of masked defect. Here, the isotropic MDF is assumed in the N region, i.e., \(\Gamma_N = 1\).

...anisotropic MDF to probe the masked atom-scale defects in the two-dimensional materials with graphene as an example.

To achieve the high-mobility, graphene is needed to be encapsulated in the insulating and atomically flat boron nitride crystals, and the encapsulated process even the mismatch between graphene and the boron nitride crystals usually brings a small amount of defects into the graphene samples\(^{35}\).

Fig. 3 schematically shows the proposed device in which an incomplete encapsulation is proposed, i.e., graphene is sandwiched between two substrates and the area of bottom substrate is larger than that of the other top one. Then, the encapsulated region and the unencapsulated region can be doped into N type and P type through the gates contacting to top and bottom substrates, i.e., a PNJ is formed. The large-area ballistic graphene is not easy to be fabricated\(^{32,33}\), so to fully utilize the ballistic nature, the encapsulated graphene should be as large as possible which leads to the small unencapsulated region for the probe. To apply the superlattice potentials\(^{5,7-36,39}\) or the strain on the substrate\(^{34}\), below the unencapsulated region, one can obtain the anisotropic MDF in the P region whose anisotropic degree \(\Gamma_P\) can be fine tuned, e.g., make \(\Gamma_P > 1\). If there is a defect denoted by the black dot at \(r_1 = (x_1, y_1)\) in the N region, due to the Veselago focusing, one can probe a focusing image denoted by the red circle at \(r_2 = (x_2, y_2) = (-x_1/\Gamma_P, y_1)\) (see Eq. 6) with the strong local density of states in the small unencapsulated region by using the scanning tunneling microscope, i.e., the realization of the probe of masked defect. Here, for the sake of simplicity, the isotropic MDF is assumed in the N region, i.e., \(\Gamma_N = 1\). In the simple case of the PNJ for the isotropic MDF, the Veselago focusing can also be as the principle to probe the masked defects, but the focusing should be at the mirror image and may be beyond the unencapsulated region, e.g., see the mirror image at \(r^*_2 = (x^*_2, y^*_2) = (-x_1, y_1)\). Therefore, the tunable focusing position of anisotropic MDF is beneficial to the probe of masked defects.

To be here, we clearly show the Veselago focusing of anisotropic MDF and the tunable features, this offers easy access to the future theoretical and experimental studies. The Veselago focusing has a lot of potential applications\(^{31,32}\). Since the Veselago focusing in the PNJ based on the anisotropic MDF shows the superior tunable features, this must also favor the relevant applications. It is convenient to expand our study to incorporate the other degrees of freedom such as spin\(^{26,25-30}\), valley\(^{25}\), to consider three-dimensional MDF\(^{31}\), and to examine the multiple junctions\(^{35}\) and even superlattices\(^{27}\), and so on. Therefore, this study opens a venue to investigate the electron optics behaviors of anisotropic MDF and the potential device applications.

**Conclusions.**—In this study, we study the propagation behaviors of anisotropic MDF in the PNJ structure. Through projecting relations between anisotropic and isotropic MDF, we analytically show the precise Veselago focusing with the superior tunable features. The tunable features certainly favor the previous proposed applications based on the Veselago focusing and bring us to design the novel device to probe the masked defect by utilizing the tunable focusing position. This study presents an innovative concept to realize the Veselago focusing beneficial to its potential applications, and opens a venue to investigate the electron optics behaviors of anisotropic MDF and the potential device applications.

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...shuhuizhang@mail.buct.edu.cn
wennyang@csrc.ac.cn

1. A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, Rev. Mod. Phys. 81, 109 (2009).
2. X.-L. Qi and S.-C. Zhang, Rev. Mod. Phys. 83, 1057 (2011).
3. V. M. Pereira and A. H. Castro Neto, Phys. Rev. Lett. 103, 046801 (2009).
4. G. G. Naumis, S. Barraza-Lopez, M. Oliva-Leyva, and H. Terrones, Reports on Progress in Physics 80, 096501 (2017).
5. C.-H. Park, L. Yang, Y.-W. Son, M. L. Cohen, and S. G. Louie, Nature Physics 4, 213 (2008).
6. C.-H. Park, L. Yang, Y.-W. Son, M. L. Cohen, and S. G. Louie, Phys. Rev. Lett. 101, 126804 (2008).
7. S. Rusponi, M. Papagno, P. Moras, S. Vlaic, M. Etzkorn, P. M. Sheverdyava, D. Pacilé, H. Brune, and C. Carbone, Phys. Rev. Lett. 105, 246803 (2010).
H.-Y. Lu, A. S. Cuamba, S.-Y. Lin, L. Hao, R. Wang, H. Li, Y. Zhao, and C. S. Ting, Phys. Rev. B 94, 195423 (2016).

A. Kobayashi, S. Katayama, Y. Suzumura, and H. Fukuyama, Journal of the Physical Society of Japan 76, 034711 (2007).

S. Banerjee, R. R. P. Singh, V. Pardo, and W. E. Pickett, Phys. Rev. Lett. 103, 016402 (2009).

P. Richard, K. Nakayama, T. Sato, M. Neupane, Y.-M. Xu, J. H. Bowen, G. F. Chen, J. L. Luo, N. L. Wang, X. Dai, et al., Phys. Rev. Lett. 104, 137001 (2010).

M. Killi, S. Wu, and A. Paramekanti, Phys. Rev. Lett. 107, 086801 (2011).

Y. J. Jo, J. Park, G. Lee, M. J. Eom, E. S. Choi, J. H. Shim, W. Kang, and J. S. Kim, Phys. Rev. Lett. 113, 156602 (2014).

C.-Y. Moon, J. Han, H. Lee, and H. J. Choi, Phys. Rev. B 84, 195425 (2011).

A. Lopez-Bezanilla and P. B. Littlewood, Phys. Rev. B 93, 241405 (2016).

Z. Li, T. Cao, M. Wu, and S. G. Louie, Nano Letters 17, 2280 (2017).

J. Park, G. Lee, F. Wolff-Fabris, Y. Y. Koh, M. J. Eom, Y. K. Kim, M. A. Farhan, Y. J. Jo, C. Kim, J. H. Shim, et al., Phys. Rev. Lett. 107, 126402 (2011).

K. Mullen, B. Uchoa, and D. T. Glatzhofer, Phys. Rev. Lett. 115, 026403 (2015).

M. Yan, H. Huang, K. Zhang, E. Wang, W. Yao, K. Deng, G. Wan, H. Zhang, M. Arita, H. Yang, et al., Nature Communications 8, 257 (2017).

T. Wehling, A. Black-Schaffer, and A. Balatsky, Advances in Physics 63, 1 (2014).

V. V. Cheianov, V. Fal’ko, and B. L. Altshuler, Science 315, 1252 (2007).

J. R. Williams, T. Low, M. S. Lundstrom, and C. M. Marcus, Nat Nano 6, 222 (2011).

P. Rickhaus, R. Maurand, M.-H. Liu, M. Weiss, K. Richter, and C. Schonenberger, Nat. Commun. 4, 2342 (2013).

T. Taychatanapat, J. Y. Tan, Y. Yeo, K. Watanabe, T. Taniguchi, and B. Özyilmaz, Nature Communications 6, 6093 (2015).

J. L. Garcia-Pomar, A. Cortijo, and M. Nieto-Vesperinas, Phys. Rev. Lett. 100, 236801 (2008).

A. Moghaddam and M. Zareyan, Phys. Rev. Lett. 105, 146803 (2010).

M. G. Silveirinha and N. Engheta, Phys. Rev. Lett. 110, 213902 (2013).

L. Zhao, P. Tang, B.-L. Gu, and W. Duan, Phys. Rev. Lett. 111, 116601 (2013).

P. Bøggild, J. M. Caridad, C. Stampfer, G. Calogero, N. R. Papior, and M. Brandbyge, Nature Communications 8, 15783 (2017).

S.-H. Zhang, J.-J. Zhu, W. Yang, and K. Chang, 2D Materials 4, 035005 (2017).

R. D. Y. Hills, A. Kustomtseva, and F. V. Kustomtsev, Phys. Rev. B 95, 214103 (2017).

G.-H. Lee, G.-H. Park, and H.-J. Lee, Nat. Phys. 11, 925 (2015).

S. Chen, Z. Han, M. M. Elahi, K. M. Habib, L. Wang, B. Wen, Y. Gao, T. Taniguchi, K. Watanabe, J. Hone, et al., Science 353, 1522 (2016).

M. Settnes, S. R. Power, D. H. Petersen, and A.-P. Jauho, Phys. Rev. Lett. 112, 096801 (2014).

C. R. Dean, A. F. Young, I. Meric, C. Lee, L. Wang, S. Sorgenfrei, K. Watanabe, T. Taniguchi, P. Kim, K. L. Shepard, et al., Nature Nanotechnology 5, 722 (2010).

C. H. Park, Y.-W. Son, L. Yang, M. L. Cohen, and S. G. Louie, Phys. Rev. Lett. 103, 046808 (2009).

L. Brey and H. A. Fertig, Phys. Rev. Lett. 103, 046809 (2009).

M. Barbier, F. M. Peeters, P. Vasilopoulos, and J. M. Pereira, Phys. Rev. B 77, 115446 (2008).

M. Barbier, P. Vasilopoulos, F. M. Peeters, and J. M. Pereira, Phys. Rev. B 79, 155402 (2009).