Generation of valley polarized current in bilayer graphene

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We propose a device for the generation of valley polarized electronic current in bilayer graphene. By analyzing the response of this material to intense terahertz frequency light in the presence of a transverse electric field we demonstrate that dynamical states are induced in the gapped energy region, and if the system parameters are properly tuned, these states exist only in one valley. The valley polarized states can then be used to filter an arbitrary electron current, so generating a valley polarized current.

One particularly interesting feature of mono- and bilayer graphene [1–3] is the valley degree of freedom. The six corners of the Brillouin zone (the K points in the inset to Fig. 1) are separated from each other in momentum space, and the geometry of the reciprocal lattice requires that opposite corners are inequivalent so that there are two species of K point, called ‘valleys’ [4]. The low energy spectrum is localized near the six K points, so that in this limit, which of the two valleys the electron momentum is located in becomes a good quantum number. The valley degree of freedom therefore constitutes a two state system (analogous to the electron spin) and is often called the ‘isospin’. This has prompted the suggestion that the isospin could be manipulated and controlled in a useful way (so-called ‘valleytronics’), for example, to make a solid state qubit [5]. Of course, in order to achieve this goal, one must be able to accurately prepare and manipulate electron states in one valley or another, and to date there have been several proposals for devices which purport to achieve this [5–10].

Recently, attention has also turned to the optical properties of monolayer graphene, and its response to linearly and circularly polarized irradiating light fields has shown interesting features resulting from the chirality of the electrons and the linear low energy spectrum [11, 12].

In this Letter, we combine these areas of interest and analyze the response of the energy spectrum of gapped bilayer graphene [2, 13] to external electromagnetic radiation in the terahertz frequency range. We then propose a device which filters electrons according to which valley they are in, creating a valley polarized current. Specifically, we find that the different sublattice composition of the wave functions of electrons in opposite valleys causes them to interact with the irradiating field asymmetrically. When the radiation and system parameters are properly tuned, dynamical states existing entirely in one valley are induced. If a current of electrons in this energy range is passed through the irradiated region, the absence of available states in one valley means that those electrons are unable to pass, while electrons in the other valley may. The current exiting the irradiated region is therefore comprised of electrons in only one valley, a so-called ‘valley polarized current’.

This filtering effect is a direct result of the valley asymmetric density of states in the irradiated region, and is therefore a bulk effect, independent of the geometry of the sample and its edges. This gives our device a significant advantage over many prior proposals as it does not rely on the precise construction of an edge (as in Refs. 5–7), or the exact deposition of a gate along one crystallographic direction (as in Ref. 8), both of which are very challenging tasks. Reference 10 also necessitates a complex gating arrangement to support one-dimensional channels in the graphene. Even if these devices could be manufactured, the currents they produce are often only partially polarized, and are localized in one-dimensional channels, whereas our proposal shows complete valley polarization for significant current flow in a bulk situation, making the potential for applications of the current generated by this device much more plausible.

We model irradiated bilayer graphene using the Hamiltonian \( \mathcal{H} = H_0 + H_U + H(t) \), where \( H_0 \) is the Hamiltonian of ungated, unirradiated graphene and \( H_U \) represents the inter-layer potential difference generated by the top gate [4]. The time dependent term \( H(t) \) is the Hamiltonian of the irradiating field, described by making the Peierls substitution in \( H_0 + H_U \) with the vector potential \( A = F/|\Omega| [\cos \Omega t, \sin \Omega t] \) (where \( \Omega \) is the frequency of the radiation) giving

\[
H(t) = \frac{\xi_{e_F} F}{|\Omega|} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \otimes \begin{pmatrix} 0 & e^{-i\Omega t} \\ e^{i\Omega t} & 0 \end{pmatrix}.
\]

The opposite orientation of the circular polarization is employed by substituting \( \Omega \rightarrow -\Omega \) in this definition. The
The time dependent Schrödinger equation for \( H \) of the Hamiltonian over the states \( \Psi \) of the dynamical state. In the left-hand column, the coupling parameter is \( x = 0.96 \) (weakly irradiated) while in the right-hand column \( x = 4.82 \) (strongly irradiated). We superimpose the unirradiated \( (F = 0) \) spectrum (red lines) for comparison. The radiation opens dynamical gaps at \( h\Omega/2 \) intervals (as was shown in the monolayer case [11]). Secondly, when there is a gate potential applied, dynamical states are present in the gapped region (see the lower two rows), and the quadratic shape of the low momentum part of the bands is restored for strong radiation. However, because \( K \) electrons couple more strongly to the radiation than \( K' \) electrons (due to the different sublattice composition of the wave functions), the weights of the static component of the Floquet states are drastically different in each valley. In the strongly irradiated regime, the notion of the static gap loses its meaning as there are many dynamical states with significant static component in that energy range. It is the dynamical states in the static gap which we utilize in the proposal for the valley filtering device. Reversing the polarization of the light or the orientation of \( U \) causes the \( K' \) valley to couple strongly.

We now demonstrate the generation of valley polarized current by using irradiated bilayer graphene as a filter for an arbitrary current. We employ a tunnelling approach [15] where we suppose that the system consists of three parts, as shown in Fig. 1. They are the two graphitic ‘leads’ described by Hamiltonians \( H_L, H_R = H_0 \) with energy spectrum \( E_\alpha \) and chemical potential \( \pm \mu/2 \), and the central, irradiated region described by the time dependent Hamiltonian \( H_C = \mathcal{H} \) discussed above, with quasienergy spectrum \( \varepsilon_\alpha \) and chemical potential fixed at zero. The contacts shown in Fig. 1 connect the graphene flake with external systems, and we do not consider their influence. The central region is linked to the leads via the coupling Hamiltonians \( H_{CL}, H_{CR} \). Denoting the operators for electrons in the leads by \( c^\dagger_{\mathbf{k}l} \) for \( i \in \{L, R\} \),

\[
\Psi_A(x, t) = \sum_{n = -\infty}^{\infty} \sum_{\alpha} e^{i n \Omega t} \chi^A_{\alpha} \psi^{(n)}_{\alpha}(x).
\]
and the central area by \( d_{qA} \), we have

\[
H_{Ci} = \sum_{k,\alpha, q, A} V_{k\alpha, q, A} c^\dagger_{k\alpha} d_{qA} + \text{H.C.}
\]

We assume that the central region is wide enough to forbid electrons from tunnelling directly between the two leads. Since it has been shown [16] that transmission from bilayer graphene into gapped bilayer graphene is high for a wide range of the electron’s angle of momentum, we assume that for the transfer to occur, the electron’s momentum is conserved and the energy of the states in the two regions must be sufficiently close. We parameterize this closeness by writing the function \( \Delta(E) \) such that \( \Delta(E) = 0 \) for \( |E| > \eta \) and \( \Delta(0) = 1 \) so that \( \eta \) describes the width of the allowed transition. Then, the coupling parameter is \( \bar{\epsilon}_{qA} = V \delta_{k, q} \Delta(E_{k\alpha} - \epsilon_{q,A}) \mid \chi_{\alpha} \rangle \langle \chi_{\alpha} \mid \). The quantity \( V \) has units of energy and parameterizes the maximal strength of the coupling and we preserve the electron momentum via the \( \delta \) function.

The valley component of the charge current in the right-hand lead is

\[
J_\xi = \frac{2e}{h} \int \frac{d^2k}{(2\pi)^2} \sum_{\alpha, \xi} \text{Tr} \left\{ \bar{\Gamma}_{\alpha, \xi} \bar{G}^\prime (E_{\alpha, \xi}) \right\} \mathcal{F}
\]

where \( \bar{G}^\prime \) is the imaginary part of the full retarded Green’s function in the central region, \( \bar{\Gamma} \) contains the coupling parameters, and \( \mathcal{F} = f_c(E_{\alpha, \xi}) - f_R(E_{\alpha, \xi}) \) depends on the distribution functions in the right lead and central region. The central region Green’s function is calculated using the Floquet states derived above, and includes the self energy due to the two leads.

To characterize the degree of valley polarization of the current, we define \( \mathcal{P} = (J_K - J_{K'})/(J_K + J_{K'}) \) so that \( \mathcal{P} = -(+1) \) corresponds to fully \( K' \) (\( K \)) polarized current. In Fig. 3 we plot the total current and the polarization as a function of the radiation intensity and frequency for \( U = 20 \text{meV} \) and the chemical potentials of the leads arranged to drive current in the energy range corresponding to the static gap (\( \mu = 12 \text{meV} \)). The area enclosed by the white contour shows where \( J > 0.04 \text{pA} \) and \( \mathcal{P} > 0.98 \) simultaneously, i.e. the region where the system parameters are tuned for significant current and very high polarization. Reversing the sign of \( U \) or the orientation of the polarization of the radiation leaves Fig. 3(i) unchanged, but inverts Fig. 3(ii) so that the region of high current and polarization is in the \( K' \) valley. Identification of the valley into which the current is polarized may be achieved by application of an in-plane electric field [7] which produces a valley-dependent Hall current which will result in a measurable asymmetry in the electron density across the conducting channel.

In summary, we have described the measurable characteristics of a graphene-based valley polarized current generator, where we expect current of \( \sim 0.1 \text{pA} \) and valley polarization of \( > 99\% \). Our work should provide necessary stimulus in the quest for valleytronics with graphene.

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[1] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, Science 306, 666 (2004); K. S. Novoselov, E. McCann, S. V. Morozov, I. V. Fal’ko, M. I. Katsnelson, U. Zeitler, D. Jiang, F. Schedin, and A. K. Geim, Nat. Phys. 2, 177 (2006).
[2] T. Ohta, A. Bostwick, T. Seyller, K. Horn, and E. Rotenberg, Science 313, 951 (2006).
[3] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos, and A. A. Firsov, Nature (London) 438, 197 (2005); Y. Zhang, Y.-W. Tan, H. Stormer, and P. Kim, ibid 438, 201.
[4] E. McCann, D. S. L. Abergel, and V. I. Fal’ko, Eur. Phys. J. Special Topics 143, 91 (2006).
[5] A. Rycerz, J. Tworzydlo, and C. W. J. Beenakker, Nat. Phys. 3, 172 (2007); A. R. Akhmerov, J. H. Bardarson, A. Rycerz, and C. W. J. Beenakker, Phys. Rev. B 77, 205416 (2008).
[6] G. Tkachov, Phys. Rev. B 79, 045429 (2009); A. Cresti, G. Grosso, and G. P. Parravicini, Phys. Rev. B 77, 233402 (2008).
[7] D. Xiao, W. Yao, Q. Niu, Phys. Rev. Lett. 99, 236809 (2007).
[8] J. M. Pereira, Jr., F. M. Peeters, R. N. Costa Filho, and G. A. Farias, J. Phys. Condens. Matter 21, 045301 (2009).
[9] J. L. Garcia-Pomar, A. Cortijo, and M. Nieto-Vesperinas, Phys. Rev. Lett. 100, 236801 (2008).
[10] I. Martin, Ya. M. Blanter, and A. F. Morpurgo Phys. Rev. Lett. 100, 036804 (2008).
[11] S. V. Syzranov, M. V. Fistul, and K. B. Efetov Phys. Rev. B 78, 045407 (2008); T. Oka, and H. Aoki, Phys. Rev. B 79, 081406(R) (2009).
[12] W. Yao, D. Xiao, and Q. Niu, Phys. Rev. B 77, 235406 (2008); F. J. López-Rodríguez and G. G. Naumis, Phys. Rev. B 78 201406(R) (2008).
[13] J. B. Oostinga, H. J. Heersche, X. Liu, A. F. Morpurgo, and L. K. Vandersypen, Nat. Mater. 7, 151 (2008); E. McCann, Phys. Rev. B 74 161403(R) (2006); E. V. Castro, K. S. Novoselov, S. V. Morozov, N. M. R. Peres, J. M. B. Lopes dos Santos, J. Nilsson, F. Guinea, A. K. Geim, and A. H. Castro Neto, Phys. Rev. Lett. 99, 216802 (2007).
[14] T. Dittrich, P. Hänggi, G.-L. Ingold, B. Kramer, G. Schön, and W. Zwerger Quantum Transport and Dissipation, Wiley-VCH (Weinheim 1998), Chapter 5.
[15] H. Haug, and A.-P. Jauho, Quantum Kinetics in Transport and Optics of Semiconductors, Springer (Berlin, 1998), Chapter 12.
[16] J. Nilsson, A. H. Castro Neto, F. Guinea, and N. M. R. Peres, Phys. Rev. B 76, 165416 (2007).