Topologically protected edge-states in disordered graphene

David Soriano[1,2], D. Gosálbez-Martínez[1], Joaquín Fernández-Rossier[1] and Juan José Palacios[3]

[1] Dpto. de Física Aplicada, Universidad de Alicante, San Vicente del Raspeig, Spain
[2] Instituto de Ciencia de Materiales de Madrid (CSIC), Cantoblanco, Madrid, Spain
[3] Dpto. de Física de la Materia Condensada, Universidad Autónoma de Madrid, Cantoblanco, Spain
David.Soriano@ua.es

Since its discovery by A. K. Geim and K. Novoselov in 2004[1], Graphene has become one of the most important materials ever synthesized, mainly due to its amazing physical properties. This two-dimensional material, only composed by carbon atoms arranged in a honeycomb lattice, has a breaking strength much higher than steel and electrons can travel through it ballistically lengths close to the sub-micrometer scale. This unusual transport property of graphene is given by the massless Dirac-like behavior the electrons acquire as they move along the lattice.

In the last years, a lot of effort has been made in order to probe magnetism in graphene-based systems. This has opened a new branch in condensed-matter physics called carbon-based spintronics[2]. In this context, hydrogenated graphene[3, 4, 5] and graphene nanoribbons[6], together with zigzag graphene nanoribbons and nanoislands[7, 8] have become the best candidates to improve magnetism in graphene. The sp3-like defects, in the case of hydrogenated graphene samples, or zigzag-shaped edges, in the case of zigzag graphene nanoribbons, give rise to zero-energy states in the electronic structure which are localized around the defects and along the edges respectively. These zero-energy states tend to spin-polarize when the Coulomb interaction is taking into account giving rise to local magnetic moments.

In 2005, Kane and Mele[9,10], included the spin-orbit coupling in Graphene by using a model Hamiltonian containing a complex second-neighbor hopping term (very similar to that used by Haldane in 1988[11] to realize the quantum Hall effect in a honeycomb lattice in the absence of an external magnetic field). By including such interaction, Graphene evolves from a normal insulator to a spin Hall insulator with topologically protected edge states against disorder which preserves time-reversal symmetry. In this context, one can refer to graphene as a Topological Insulator[12]. In this novel phase, the edge states become spin-filtered in the sense that spin-up electrons goes forward in the upper edge and backward in the bottom edge, and inversely for spin-down electrons (Figure 1).

Here we address the electronic properties of a zigzag graphene nanoribbon when both Coulomb repulsion and spin-orbit coupling are considered within **(a)** a mean field Hubbard model with Kane-Mele spin-orbit interaction[13] and **(b)** a tight-binding model within the Slater-Koster approximation where the spin-orbit coupling is introduced by means of an intra-atomic potential[14]. We find that **(1)** spin-orbit interaction give rise to topologically protected edge states against different kind of disorder as Anderson-like or edge disorder (Figure 2a), **(2)** in the presence of spin-orbit coupling the ground state with counter-polarized ferromagnetic edges breaks valley symmetry and, above a critical spin-orbit strength, the gap closes in one valley only, resulting in a valley half-metal (Figure 2b), and **(3)** in the presence of spin-orbit coupling ferromagnetic edges give rise to charge currents in the edges reaching 0.4 nA without an applied magnetic field (Figure 2c).

References

[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** (2004) 666.
[2] O. V. Yazyev, Rep. Prog. Phys., **73** (2010) 056501.
[3] O. V. Yazyev and L. Helm, Phys. Rev. B, **75** (2007) 125408.
[4] D. C. Elias, R. R. Nair, T. M. G. Mohiuddin, S. V. Morozov, P. Blake, M. P. Halsall, A. C. Ferrari, D. W. Boukhvalov, M. I. Katsnelson, A. K. Geim and K. S. Novoselov, Science, **323** (2009) 610.
[5] S. Casolo, O. M. Løvvik, R. Martinazzo and G. F. Tantardini, J. Chem. Phys., **130** (2009) 054704.
[6] D. Soriano, F. Muñoz-Rojas, J. Fernández-Rossier and J. J. Palacios, Phys. Rev. B, **81** (2010) 165409.
[7] F. Muñoz-Rojas, J. Fernández-Rossier and J. J. Palacios, Phys. Rev. Lett., **102** (2009) 136810.
[8] J. Fernández-Rossier and J. J. Palacios, Phys. Rev. Lett., **99** (2007) 177204.
[9] C. L. Kane and E. J. Mele, Phys. Rev. Lett., **95** (2005) 226801.
[10] C. L. Kane and E. J. Mele, Phys. Rev. Lett., **95** (2005) 146802.
[11] F. D. M. Haldane, Phys. Rev. Lett., **61** (1988) 2015.
[12] B. A. Bernevig, T. L. Hughes and S. C. Zhang, Science, **314** (2006) 1757.
[13] D. Soriano and J. Fernández-Rossier, Phys. Rev. B, **81** (2010) 161302.
[14] D. Gosálbez-Martínez, J. J. Palacios and J. Fernández-Rossier, arXiv:1012.0228v1.

Figures

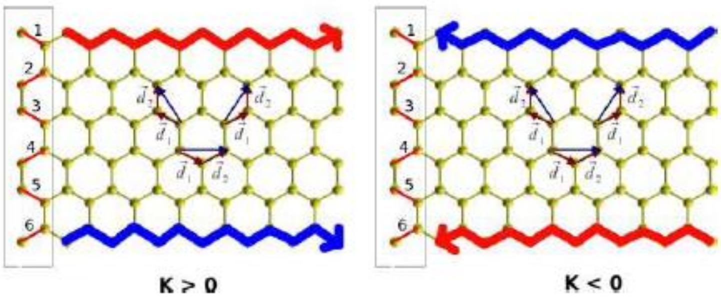

Figure 1. Pictorial description of the spin-orbit term of the Kane-Mele Hamiltonian where the second neighbors are connected along the two nearest neighbor bonds $\vec{d}_1$ and $\vec{d}_2$. It is also shown how electrons with opposite spins (blue and red arrows) propagate in opposite directions in each valley.

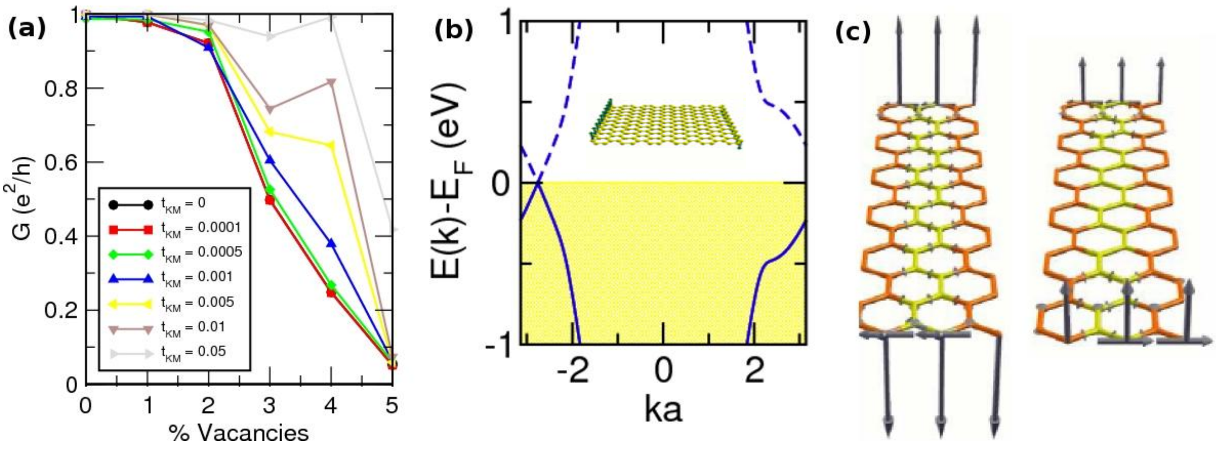

Figure 2. (a) The conductance decreases rapidly as the percentage of vacancies is increased at the edges. Still, it is always possible to find a value of the spin-orbit coupling for which the edge states are preserved and the conductance approach 1 G_0. (b) For certain values of the spin-orbit coupling, the band structure of zigzag graphene nanoribbons with counterpolarized ferromagnetic edges breaks valley-symmetry giving rise to a valley half-metal. (c) Current and magnetization maps for antiferromagnetic and ferromagnetic zigzag ribbons computed using the Kane-Mele-Hubbard model. Charge currents in the edges approach 0.4 nA without an applied magnetic field.