Topological features and gauge fields in graphene superlattices.

Detecting Topological Currents in Graphene Superlattices
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Recommended with a commentary by Francisco Guinea, CSIC.

The quest for crystals whose electronic bands show non trivial topological features has not ceased since the discovery of the Quantum Hall Effect. The amazing current quantization in QHE devices can be traced back to edge states which emerge from non trivial electronic structures[1, 2]. Topological properties are typically associated to integer numbers, so that they are quite robust against perturbations. The search for such systems culminated in the development of the concept of the topological insulator[3, 4] (TI).A two dimensional TI can be viewed as two copies of a Quantum Hall system, related by time reversal symmetry (TRS). In the absence of perturbations which break TRS, each copy should show quantized electronic transport, as in the Integer Quantum Hall Effect.

The topology of a given (isolated) electronic band in a two dimensional system is described by an integral over the Brillouin Zone[5]. The integrand is determined by the momentum dependence of the wavefunction. The value of this integral must be an integer, the Chern number. The simplest bands with non trivial Chern numbers are the Landau levels induced by a constant magnetic field in a two dimensional electron gas. Alternatively, some relatively simple singularities in band structures, like gapped Dirac points in triangular lattices, lead to non trivial integrands, which, in turn, may give rise to non zero Chern numbers[2, 3]. Bands associated to a single atomic orbital in the unit cell cannot have a non trivial topology.

Graphene is a material with Dirac cones precisely at the Fermi level. It combines interesting fundamental properties, amazing resilience, and little disorder. In fact, the band structure of graphene is behind some of the proposals described above[2, 3]. Including spin and valley degeneracy, graphene has four Dirac cones. The region in momentum space near the apex of each cone contributes the the integrated Chern number of the valence and conduction bands with $\pm 1/2$. In order to turn graphene into a system with non trivial topology i) the Dirac cones need to be gapped, and ii) the contribution from each cone needs to have the right sign, so that no cancellations occur. The realization of these premises is a tall order: ordinary gaps in graphene require the absence of spatial inversion symmetry, and TRS implies that the sum of the contributions from all cones vanishes. The way out of this dilemma proposed in[3] was the formation of gaps by the spin-orbit interaction. Each spin band becomes topologically non trivial, and graphene turns into a TI. Unfortunately, carbon is a

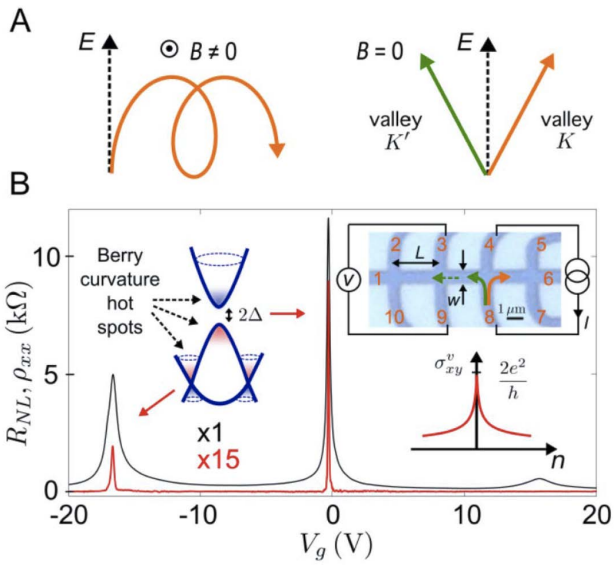

Figure 1: Top: Sketch of the non local currents induced in the experiments discussed here. Bottom: Measured dependence of non local currents on gate voltage. Taken from Fig. 1 in the paper in the title of this commentary.

light element, relativistic effects are small, and the spin orbit coupling is only relevant at extremely small scales $\sim \mu$eV, where it will be obscured by residual disorder.

There is another, simpler, route to achieve a non a trivial topology in graphene, although with features less robust than those of the IQHE and the TI's. The trajectories of carriers with momentum near a Dirac cone are modified in a similar way to what happens in the IQHE[5, 6]. Time Reversal Symmetry, however, implies that the induced Hall resistance has opposite signs in the two valleys. Provided that the Dirac cones are gapped, and that disorder does not scatter the electrons from a Dirac cone to the other, graphene is equivalent to two decoupled systems with interesting topological features. Similarly to the IQHE electrons from different valleys will accumulate in opposite edges.

The paper discussed here gives convincing experimental evidence, and solid theoretical arguments, that this situation has been observed. The system used is a graphene layer on a BN substrate. Previous experiments have shown unambiguously that, when the two sublattices are aligned, the substrate defines an electronic superlattice with a large lattice parameter[7, 8, 9, 10], $\sim$ 10nm. The BN substrate lacks inversion symmetry, and a number of mechanisms can open a gap[11, 12, 13]. The graphene π band is broken into superlattice minibands with finite Chern numbers[12, 13, 14]. The experiments reported in the paper suggest

gaps of order 20-30 meV, in agreement with other experiments[10] (it is interesting to note that theoretical estimates give smaller gaps). The experiments are carried out slightly away from the neutrality point, where a few carriers populate the lowest valence or conduction subbands, the so called topological conductor regime. Transport properties are mainly determined by bulk currents. Carriers in different valleys experience a lateral force which gives rise to motion normal to the applied field. These currents induce non local effects, that is, voltages at contacts removed from the main current path. The paper analyzes carefully these non local effects, which are only found in a narrow density and temperature range, consistent with expectations. Non local effects are found to exist over distances of order of 10μm, while resistivities suggest a transport mean free path at least one order of magnitude lower. This result corroborates other transport experiments, such as Weak Localization measurements, which indicate that electronic transport in graphene is mostly limited by intra-valley scattering. A sketch of the current distribution, as ell as experimental results, taken from this work, are shown in Fig.[1].

It is finally worth mentioning that a whole family of two dimensional compounds, the transition metal dichalcogenides, MoS_2, WS_2, ... have gapped valleys, lack inversion symmetry, and have spin split bands due to a significant spin-orbit interaction. Hence, superlattices based on these materials can become topological insulators.

References

[1] D. J. Thouless, D. J., M.Kohmoto, M. P. Nightingale, and M. den Nijs, Phs. Rev. Lett. **49**, 405 (1982).

[2] F. D. M. Haldane, Phys. Rev. Lett. **61**, 2015 (1988).

[3] C. L. Kane, and E. J. Mele, Phys. Rev. Lett. **95**, 226801 (2005).

[4] B. Andrei Bernevig, and Shou-Cheng Zhang, Phys. Rev. Lett. **95**, 016801 (2005).

[5] D. Xiao, M.-C. Chang, and Q. Niu, Rev. Mod. Phys. **82**, 1959 (2010).

[6] D. Xiao, W Wang, and Q. Niu, Phys. Rev. Lett. bf 99, 236809 (2007).

[7] M. Yankowitz, J. Xue, and D. Cormode, J. D. Sanchez-Yamagishi, K. Watanabe, T. Taniguchi, P. Jarillo-Herrero, P. Jacquod, and B. J. LeRoy, Nature Phys. **8**, 382 (2012).

[8] L. A. Ponomarenko, R. V. Gorbachev, D. C. Elias, G. L. Yu, A. S. Mayorov, J. Wallbank, M. Mucha-Kruczynski, A. Patel, B. A. Piot, M. Potemski, I. V. Grigorieva, K. S. Novoselov, F. Guinea, V. I. Fal'ko, and A. K. Geim, Nature **497**, 594 (2013).

[9] , C. R. Dean, L. Wang, P. Maher, C. Forsythe, F. Ghahari, Y. Gao, J. Katoch, M. Ishigami, P. Moon, M. Koshino, T. Taniguchi, K. Watanabe, K. L. Shepard, J. Hone, P. Kim, Nature **497**, 598 (2013).

[10] B. Hunt, J. D. Sanchez-Yamagishi, A. F. Young, M. Yankowitz, B. J. LeRoy, K. Watanabe, T. Taniguchi, P. Moon, M. Koshino, P. Jarillo-Herrero, and R.C. Ashoori, Science **340**, 1427 (2013).

[11] J. C. W. Song, A. V. Shytov, and L. S. Levitov, Phys. Rev. Lett. **111**, 266801 (2013).

[12] J. Jung, A. DaSilva, A. H. MacDonald, and S. Adam, arXiv:1403.0496, (2014),

[13] P. San-Jose, Á. Gutiérrez, M. Sturla, and F. Guinea, Phys. Rev. B **90**, 075428 (2014).

[14] J. C. W. Song, P. Samutpraphoot, and L. S. Levitov, arXiv:1404.4019 (2014).