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Proximity-induced spin-orbit and exchange coupling in graphene-based heterostructures

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Chapter 9

Outlook

Abstract

Van der Waals heterostructures provide us with an open platform to design new materials with unlimited properties and functionalities. In particular the experimental realization of the various phenomena emerged in graphene as a direct signature of the induced SOC or magnetism assures that we can efficiently modify the Dirac states of graphene. However, we are still in the early stage of implementation of the arising functionalities and there is still a lot of room for improvement of the efficiency of the observed phenomena. In this chapter we review some of the theoretically suggested heterostructure designs or experiments that can allow for further electrical tunability of the induced spin-orbit and exchange coupling in graphene. The experimental investigations of the effects proposed here are yet to be performed as the follow-up of the studies in this thesis.

Gate-tunable spin-lifetime anisotropy

The strong anisotropy of the spin lifetime, reported in chapter 6 and also in Ref. [1] can act as a spin filter in spintronic circuitry where the transmission depends on the effective orientation of the spins [2]. Having the lifetime of the out-of-plane spins to be at least one order of magnitude larger than that of the in-plane spins implies that any slight variation of the spin orientation can be detected in such spin filters. It is expected that the strength of the induced SOC in graphene and thus the magnitude of the spin-lifetime anisotropy can be tunable with a transverse electric field. That would allow for the electrical control over the spin-filtering in the graphene-TMD vdW heterostructures which is still to be investigated. Such experiments have to be done with monitoring the charge-transport through the TMD, assuring that the Fermi energy lies within the TMD band gap to suppress the spin-sinking effect at the graphene-TMD interface. The large gate-tunable spin lifetime anisotropy is also expected in graphene in the proximity of topological insulators that is calculated to reach the values as large as $\tau_\perp/\tau_\| \sim 1000$ [3] which is to be experimentally measured. Note that the magnitude of the anisotropy is strongly dependent on the intervalley and intravalley scattering. Thus the quality of the sample can play a considerable role in reaching different anisotropy regimes [4].

Gate-tunable spin polarization of conductivity

As shown in chapter 8, the strong induced exchange coupling in graphene results in a finite spin polarization of the conductivity due to the imbalance in the carrier density with the two spin species. Even in a simplified model of considering energy-independent exchange splitting in graphene band structure, the spin-polarization of conductivity has to be efficiently tunable by changing the Fermi energy and is expected to change sign depending on whether we address electrons or holes. This is yet to be explored by top-gating the graphene channel on the magnetic substrate, as a follow-up of the study in chapter 8. Moreover the usage of only Au electrodes for the Co-free spin injection in a magnetic graphene should be possible and is yet to be explored.

Gate-tunable spin-splitting in bilayer graphene

In terms of proximity effects, bilayer graphene has unique advantages compared with monolayer graphene. The short-range proximity effects differentiate the two layers of a bilayer graphene, with the spin-orbit or exchange field being majorly induced in the layer that is closer to the interface. On the other hand the built-in electric field at the interface makes the low energy bands layer-polarized, meaning that the valence band is mainly formed by the graphene layer closer to the interface. This results in a strong electron-hole asymmetry of the spin-splitting in the bilayer graphene band structure which depends on the built-in electric field at the interface. That implies the possibility for efficient tunability of the spin-splitting by an external electric field where the spin-orbit and exchange coupling can be switched on and off for the conduction electrons [5, 6]. This can be addressed by spin-transport or weak anti-localization measurements in double-gated samples where there is a control over the external electric field, while the carrier density is kept constant [7, 8].

Swapping spin-orbit and exchange coupling in bilayer graphene

In case of having a bilayer graphene, encapsulated between a TMD and a magnetic material, each of the two graphene layers would have distinct properties in terms of the induced SOC and magnetism. As mentioned earlier the direction of the out-of-plane electric field in this heterostructure defines whether the valence or conduction bands are affected by either of the induced effects. This would allow for bifunctional so-called “ex-so-tic” devices, where both exchange and spin-orbit couplings are present in a single channel and one can swap between the two by an external electric field [9].

Bilayer graphene encapsulated with 2D magnets

The proposed spin-valve device in this case involves the encapsulation of a bilayer graphene in between two magnetic materials. The DFT calculations of the bilayer graphene band structure suggest considerable dependence of its bandgap (at the K points) on the relative orientation of the magnetic layers (on top and below the bilayer graphene). While the bilayer graphene remains conducting in the parallel magnetization configuration of the magnetic layers, a bandgap opens in an anti-parallel configuration that suppresses the conductivity [10, 11].

Electrical tunability of magnetism in 2D magnetic materials

So far it is experimentally shown that it is possible to electrically tune magnetism in 2D magnetic materials, probed recently by magneto-optical Kerr effect microscopy [12] and magnetic circular dichroism [13]. The observed voltage-controlled switching between the antiferromagnetic and ferromagnetic states, provides us with another knob for the electrical control of the spin-logic systems. Thus, for the case of a vdW stack of graphene with the 2D magnetic materials we can tune the induced magnetism in the graphene channel by gating the 2D magnet. Such gate tunability of magnetism is also expected in CrSBr [14] and it can be considered as the follow-up of the experiments in chapter 8.

Twistronics

It is shown that the strength of the induced SOC depends on the crystallographic orientation of the TMD and graphene. The relative orientation of the 2D crystals can greatly increase/decrease the spin-splitting in graphene by ten times. Depending on the twist-angle either of the Rashba or valley-Zeeman SOC can get dominant in the graphene [15–17]. This is also shown for the case of bilayer graphene, encapsulated with two layers of TMDs, where the opposite valley-Zeeman fields in the two sheets of the bilayer graphene can turn off the spin-splitting (away from the K points) [11]. There are also studies on the twist-engineering of the electronic band structure of the other vdW materials, such as TMD-2D magnet heterostructures where the breaking of the valley degeneracy in the TMD can be tuned by the twist-angle and gate electric field [18].

Effects of pressure and strain in 2D materials

In practice, the fabrication of vdW heterostructures can involve stress and strain on the crystal structure of the 2D materials. It is calculated that a biaxial strain applied to a monolayer TMD can induce considerable changes in the orbital and spin-orbit properties [17, 19]. This, together with the strong dependence of the strength of the induced SOC on the interlayer spacing in the vdW stack, would require further exploration of the environmental effects. For instance, the influence of mechanical and hydrostatic pressure during the stacking procedure or electrical measurements can be further explored [20, 21].

In addition to what is mentioned above, the induced exchange and spin-orbit coupling in 2D Dirac materials is also a platform for studying other quantum mechanical phenomena such as quantum anomalous Hall effect [22] and topologically protected chiral spin textures [23].

Bibliography

[1] L. A. Benítez, J. F. Sierra, W. S. Torres, A. Arrighi, F. Bonell, M. V. Costache, and S. O. Valenzuela, "Strongly anisotropic spin relaxation in graphene–transition metal dichalcogenide heterostructures at room temperature," *Nature Physics* **14**(3), pp. 303–308, 2018.

[2] H. Dery, H. Wu, B. Ciftcioglu, M. Huang, Y. Song, R. Kawakami, J. Shi, I. Krivorotov, I. Zutic, and L. J. Sham, "Nanospintronics based on magnetologic gates," *IEEE Transactions on Electron Devices* **59**(1), pp. 259–262, 2011.

[3] K. Song, D. Soriano, A. W. Cummings, R. Robles, P. Ordejón, and S. Roche, "Spin proximity effects in graphene/topological insulator heterostructures," *Nano Letters* **18**(3), pp. 2033–2039, 2018.

[4] A. W. Cummings, J. H. Garcia, J. Fabian, and S. Roche, "Giant spin lifetime anisotropy in graphene induced by proximity effects," *Physical Review Letters* **119**(20), p. 206601, 2017.

[5] M. Gmitra and J. Fabian, "Proximity effects in bilayer graphene on monolayer $\mathrm{WSe_2}$: field-effect spin valley locking, spin-orbit valve, and spin transistor," *Physical Review Letters* **119**(14), p. 146401, 2017.

[6] K. Zollner, M. Gmitra, and J. Fabian, "Electrically tunable exchange splitting in bilayer graphene on monolayer $\mathrm{Cr_2X_2Te_6}$ with X= Ge, Si, and Sn," *New Journal of Physics* **20**(7), p. 073007, 2018.

[7] P. Michetti and P. Recher, "Spintronics devices from bilayer graphene in contact to ferromagnetic insulators," *Physical Review B* **84**(12), p. 125438, 2011.

[8] J. Amann, T. Völkl, D. Kochan, K. Watanabe, T. Taniguchi, J. Fabian, D. Weiss, and J. Eroms, "Gate-tunable spin-orbit-coupling in bilayer graphene-$\mathrm{WSe_2}$ heterostructures," *arXiv preprint arXiv:2012.05718* , 2020.

[9] K. Zollner, M. Gmitra, and J. Fabian, "Swapping exchange and spin-orbit coupling in 2D van der Waals heterostructures," *Physical Review Letters* **125**(19), p. 196402, 2020.

[10] C. Cardoso, D. Soriano, N. García-Martínez, and J. Fernández-Rossier, "Van der Waals spin valves," *Physical Review Letters* **121**(6), p. 067701, 2018.

[11] K. Zollner and J. Fabian, "Bilayer graphene encapsulated within monolayers of $\mathrm{WS_2}$ or $\mathrm{Cr_2Ge_2Te_6}$: Tunable proximity spin-orbit or exchange coupling," *arXiv: 2103.15378* , 2021.

[12] B. Huang, G. Clark, D. R. Klein, D. MacNeill, E. Navarro-Moratalla, K. L. Seyler, N. Wilson, M. A. McGuire, D. H. Cobden, D. Xiao, *et al.*, "Electrical control of 2D magnetism in bilayer $\mathrm{CrI_3}$," *Nature Nanotechnology* **13**(7), pp. 544–548, 2018.

[13] S. Jiang, L. Li, Z. Wang, K. F. Mak, and J. Shan, "Controlling magnetism in 2D $\mathrm{CrI_3}$ by electrostatic doping," *Nature Nanotechnology* **13**(7), pp. 549–553, 2018.

[14] H. Wang, J. Qi, and X. Qian, "Electrically tunable high Curie temperature two-dimensional ferromagnetism in van der Waals layered crystals," *Applied Physics Letters* **117**(8), p. 083102, 2020.

[15] Y. Li and M. Koshino, "Twist-angle dependence of the proximity spin-orbit coupling in graphene on transition-metal dichalcogenides," *Physical Review B* **99**(7), p. 075438, 2019.

[16] A. David, P. Rakyta, A. Kormányos, and G. Burkard, "Induced spin-orbit coupling in twisted graphene-transition metal dichalcogenide heterobilayers: Twistronics meets spintronics," *Physical Review B* **100**(8), p. 085412, 2019.

[17] A. Pezo, Z. Zanolli, N. Wittemeier, A. Fazzio, S. Roche, and J. H. Garcia, "A twist for tuning the spin-orbit coupling in graphene/transition metal dichalcogenide heterobilayers," *arXiv preprint arXiv:2011.06714* , 2020.

[18] K. Zollner, P. E. F. Junior, and J. Fabian, "Proximity exchange effects in $\mathrm{MoSe_2}$ and $\mathrm{WSe_2}$ heterostructures with $\mathrm{CrI_3}$: Twist angle, layer, and gate dependence," *Physical Review B* **100**(8), p. 085128, 2019.

[19] K. Zollner, P. E. F. Junior, and J. Fabian, "Strain-tunable orbital, spin-orbit, and optical properties of monolayer transition-metal dichalcogenides," *Physical Review B* **100**(19), p. 195126, 2019.

[20] B. Fülöp, A. Márffy, E. Tóvári, M. Kedves, S. Zihlmann, D. Indolese, Z. Kovács-Krausz, K. Watanabe, T. Taniguchi, C. Schönenberger, *et al.*, "Transport measurements on van der Waals heterostructures under pressure," *arXiv preprint arXiv:2103.14617* , 2021.

[21] B. Fülöp, A. Márffy, S. Zihlmann, M. Gmitra, E. Tóvári, B. Szentpéteri, M. Kedves, K. Watanabe, T. Taniguchi, J. Fabian, *et al.*, "Boosting proximity spin orbit coupling in graphene/$\mathrm{WSe_2}$ heterostructures via hydrostatic pressure," *arXiv preprint arXiv:2103.13325* , 2021.

[22] Z. Qiao, W. Ren, H. Chen, L. Bellaiche, Z. Zhang, A. MacDonald, and Q. Niu, "Quantum anomalous Hall effect in graphene proximity coupled to an antiferromagnetic insulator," *Physical Review Letters* **112**(11), p. 116404, 2014.

[23] Z. Qiao, S. A. Yang, W. Feng, W.-K. Tse, J. Ding, Y. Yao, J. Wang, and Q. Niu, "Quantum anomalous Hall effect in graphene from Rashba and exchange effects," *Physical Review B* **82**(16), p. 161414, 2010.