Towards Room Temperature Quantum Spin Hall Effect in 2-dimensionnal Atomic Layers

Quantum Spin Hall materials (QSH materials) have attracted great interest for their specific electronic structure: QSH materials are insulating in the bulk and exhibit characteristic helical spin-polarized edge states connecting valence and conduction bands. Furthermore, these edge states are topologically protected from backscattering by time-reversal symmetry. Thus, these materials hold the promise of revolutionary spintronics devices with dissipation less spin currents or for the realization of Majorana bound states at the interface with superconductors [1].

Quantum Spin Hall effect was first predicted by Kane and Mele in graphene for which spin-orbit coupling (SOC) opens a gap at the Dirac points [2]. However, due to weak SOC in carbon, the associated band gap is too small (in the order of 10^{-3} meV) to lead to detectable QSH effect in graphene even at very low temperatures.

The main issue is thus to get QSH materials having a gap large enough to allow QSH effect at 'reasonable' temperature, ideally at room temperature.

As the gap size depends, among others, on the SOC strength associated to the elements in the QSH material, it is natural to look for materials made of heavy elements. Following the example of graphene, other group-IV 2D materials, such as silicene, or germanene have already been experimentally realized and explored. The associated gaps are higher than for graphene, however, they remain too small for potential applications [3].

On the other hand, heavier group-IV elements, like Sn or Pb were predicted to show stable 2D phases exhibiting topological properties with a band gap up to 1 eV for Pb QSH phase. However, the experimental investigations of this system are still scarce with, to our knowledge, only evidence of the formation of so called "plumbene"or stanene on metallic substrates [4,5]. To go further and characterise the electronic properties of these layers, it will be essential to transfer it to an insulating or semiconducting substrate, which can represent a major difficulty.

Thus, the ideal case would be to synthetize the honeycomb layers directly on a semiconducting or isolating substrate.

In this context, we realized first experimental studies on atomic layers of the "heavy" group-IV atoms on silicon carbide substrates. By combining Scanning Tunneling Microscopy (STM) and Grazing Incidence X-Ray Diffraction (GIRXD) we could evidence new phases of interest, one of which presenting a honeycomb structure.

These new promising phases need further exploration, more particularly of their electronic properties.

During this research project we will focus on the determination of the electronic structure of these 2D layers both at a global and local scale. More specifically, the global band structure of the 2D layers will be investigated by Spin- and Angle-Resolved Photoemission Spectroscopy (SARPES). The method provides direct determination of the spin-polarized band diagram that probes both dispersion curves and the spin-orientations of electrons. Scanning Tunneling Spectroscopy (STS) measurements will be performed to determine the electronic properties at the atomic scale: value of eventual band gaps, edge states, 1D character and spin polarization of the conducting states…

Depending on the results obtained, other issues such as superconductivity properties or modification of the electronic structure by functionalization of the 2D layers will be addressed [6].

During this doctoral research project, the student will have access to a powerful combination of complementary experimental techniques:

- SARPES setup at the Institute for Solid State Physics, the University of Tokyo. The "home-build" SARPES machine allows to map the spin-polarized band diagram of a sample with the best energy resolution (1.7 meV) in the world [7]. The system is equipped with an *in-situ* surface preparation chamber and with the time-resolved extension that probes both the filled and empty states [8]. Temperature of a sample can be varied from room temperature to a level of liquid helium that is generated in the institute.

- *STM setup for STS measuments at Paris Institute for Nanosciences, Sorbonne University*. The Spectroscopy of Novel Quantum States team at INSP has 3 microscopes, 2 of them being particularly adapted for high-resolution spectroscopy maps. One is a low-temperature STM commercial setup allowing measurements down to 4K. The other one is a 'home-build' setup working down to 300mK and working under magnetic field up to 8T. Both microscopes are fully equipped for in-situ surface / layer preparation under ultra-high vacuum conditions.

Proposals to access synchrotron radiation centers in Japan or Europe might also be submitted.

<u>Applicant skills</u>: The candidates should have a sufficient background in solid states physics and basic knowledge of surface science methods, in particular scanning tunnelling microscopy and angle resolved photoemission spectroscopy. A strong interest in experimental physics is necessary. Dynamism, autonomy, high work capacity as well as good written / oral and synthesis skills are also expected.

[1] L. Fu, C. L. Kane, Phys. Rev. Lett. 100, 096407 (2008)
[2] C. L. Kane & E. J. Mele, Phys. Rev. Lett. 95, 226801 (2005)
[3] S. Li and L. Zhang, Mat. Research Express 6, 025031 (2018)
[4] J. Deng *et al.*, Nature Materials 17, 1081 (2018)
[5] G. Bihlmayer *et al.*, Phys. Rev. Let. 124, 126401 (2020)
[6] Y. Lu et al., Sci Rep 6, 21723 (2016)
[7] K. Yaji *et al.,* Rev. Sci. Instrum. 87, 053111 (2016).
[8] K. Kawaguchi *et al.,* Rev. Sci. Instrum. 94, 083902 (2023).