2024-2027

PhD proposal

Campus Pierre et Marie Curie
Tower 23 – 3rd floor – 23-22
Director: Massimiliano Marangolo

Exploring 2D topological insulators with epitaxial stanene

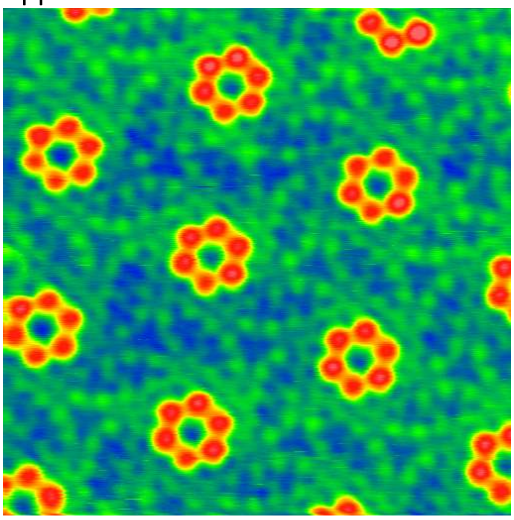
Aim

Stanene is the analogue of graphene with Sn atoms. Due to spin-orbit coupling, a gap of 72 meV is expected, that open the possibility of exploiting quantum spin hall effects on this material. The objective of the thesis is to synthesize novel 2D lattices with interesting topological properties from stanene epitaxial growth on metal and semi-conducting substrates.

Scientific context

Among two-dimensional (2D) materials, 2D topological insulators (TI) attract a great interest both from a fundamental and technological point of view. Indeed, TI often exhibit unconventional electronic properties, such as quantum anomalous Hall effect [1] valley Hall effect [2] and quantum spin Hall effect [3]. TI possess conductive edge states that are topologically protected, making them robust against disorder and perturbations, and making TI candidates for spintronic or quantum computing applications.

Examples of 2D TI are given by graphene and other honeycomb monoelemental layers such as silicene or germanene (see Fig.). They belong to the class of first order TI (FOTI), i.e. they possess protected states of dimension d-n, with n=1, where d is the material dimensionality. More recently, another class of TI has emerged: Higher Order TI (HOTI), that possess protected states of dimension d-n [4] For example, 3D bismuth has been evidenced as a HOTI [5]. For a 2D TI of 2nd order, the protected states are 0D and correspond to corner states. In order to realize HOTI, various lattices beyond the honeycomb one have been studied in relation with their topological properties [6,7] but no experimental evidence of a 2D HOTI has been given up to now.



Germanene on Ag(111), size of the image: 6.7x6.7 nm^2 ©insp

Sn appears as well adapted to explore a large variety of atomic 2D structures. The growth of honeycomb stanene lattices has been reported on various substrates, with a wide range of preparation conditions [8]. Whereas intermixing cannot be excluded for growth at room temperature (RT) or above, low temperature (LT) growth ensures the formation of a pure and ordered Sn layer. This unique characteristic makes Sn the best candidate for exploring 2D monolayers with a single element.

Method:
In this thesis, various experimental techniques will be used. At the INSP, we will used real-time scanning tunneling microscopy (STM) to follow the evolution of the surface during Sn evaporation at various temperatures. The objective is to follow simultaneously the formation of the stanene layer and the evolution of the substrate in order to determine the interaction between the layer and the metal surface. Scanning Tunneling Spectroscopy (STS) measurements will be performed at low temperature after growth in order to gain informations on the electronic properties of the layer grown.
We also intend to perform experiments on synchrotron radiation facilities, such as SOLEIL synchrotron. In particular, surface X-ray diffraction (SXRD) will allow us to determine the precise atomic structure of the synthesized layers, while angle-resolved X-ray photoemission spectroscopy (ARPES) will give us the electronic structure of the epitaxial stanene. Collaborations with the theoretician group of IS2M (Mulhouse), with the Surfaces, Spectroscopies and Modeling group of IJL (Nancy) are also planned for modeling the structure and electronic properties and for ARPES measurements.

Research plan with provisional calendar
First year: The first year will be focused on the training of the student to STM/STS, and to complementary surface analysis tool (low energy electron diffraction/Auger electron spectroscopy). Growth of Sn on well-chosen metal surfaces will be performed at different temperatures. Proposals will be submitted on synchrotrons. Main expected result: determination of the Sn lattices and choice of surfaces for exploring the structural and electronic properties.

Second year: Growth of Sn on semi-conducting (SC) surfaces will be studied at INSP. ARPES and SXRD experiments will be performed on Sn/metal surface. Proposals will be submitted on synchrotrons. Main expected results: determination of the structure and electronic properties of Sn/metal surfaces chosen. Determination of the lattices of Sn on SC surfaces and choice of surfaces for exploring the structural and electronic properties.

Third year: ARPES and SXRD experiments will be performed of Sn/SC lattices. Complementary STM experiments may be also done at INSP, depending on the results obtained previously. The last 6 months will be focused on thesis writing and defense preparation. Main expected results: structure and electronic properties of Sn/SC surfaces.

Techniques/methods in use: scanning tunneling microscopy, surface X-ray diffraction, angle-resolved photoemission spectroscopy

Applicant skills: Motivation for experimental work, curiosity basic knowledge in condensed matter physics.

PhD supervisor: Geoffroy PREVOT, prevot@insp.jussieu.fr
PhD co-supervisor: Romain BERNARD, romain.bernard@insp.jussieu.fr

Web site: https://w3.insp.upmc.fr/recherche-2/equipes-de-recherche/physico-chimie-et-dynamique-des-surfaces/physico-chimie-et-dynamique-des-surfaces-materiaux-2d/

PhD location: Sorbonne Université, campus Pierre et Marie Curie, 4 place Jussieu, Paris

Funding considered : application to Doctoral School (ED 397)

References

(1) Haldane, F. D. M. Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the "Parity Anomaly." Phys. Rev. Lett. 1988, 61 (18), 2015–2018. https://doi.org/10.1103/PhysRevLett.61.2015.

(2) Semenoff, G. W.; Sodano, P. Non-Abelian Adiabatic Phases and the Fractional Quantum Hall Effect. Phys. Rev. Lett. 1986, 57 (10), 1195–1198. https://doi.org/10.1103/PhysRevLett.57.1195.

(3) Kane, C. L.; Mele, E. J. Quantum Spin Hall Effect in Graphene. Phys. Rev. Lett. 2005, 95 (22), 226801. https://doi.org/10.1103/PhysRevLett.95.226801.

(4) Schindler, F.; Cook, A. M.; Vergniory, M. G.; Wang, Z.; Parkin, S. S. P.; Bernevig, B. A.; Neupert, T. Higher-Order Topological Insulators. SCIENCE ADVANCES 2018.

(5) Schindler, F.; Wang, Z.; Vergniory, M. G.; Cook, A. M.; Murani, A.; Sengupta, S.; Kasumov, A. Yu.; Deblock, R.; Jeon, S.; Drozdov, I.; Bouchiat, H.; Guéron, S.; Yazdani, A.; Bernevig, B. A.; Neupert, T. Higher-Order Topology in Bismuth. Nature Phys 2018, 14 (9), 918–924. https://doi.org/10.1038/s41567-018-0224-7.

(6) Ezawa, M. Higher-Order Topological Insulators and Semimetals on the Breathing Kagome and Pyrochlore Lattices. Phys. Rev. Lett. 2018, 120 (2), 026801. https://doi.org/10.1103/PhysRevLett.120.026801.

(7) Matsumoto, D.; Mizoguchi, T.; Hatsugai, Y. Higher-Order Topological Insulator on a Martini Lattice and Its Square Root Descendant. J. Phys. Soc. Jpn. 2023, 92 (3), 034705. https://doi.org/10.7566/JPSJ.92.034705.

(8) Ochapski, M. W.; de Jong, M. P. Progress in Epitaxial Growth of Stanene. Open Physics 2022, 20 (1), 208–223. https://doi.org/10.1515/phys-2022-0021.