Investigation of two-dimensional topological insulator candidate, Pt_2HgSe_3

Nemes-Incze Péter, Head of the Topology in Nanomaterials Research Group
Institute of Technical Physics and Materials Science,
Centre for Energy Research
Eötvös Lóránd Research Network; Hungary
www.nemeslab.com

Kandrai Konrád, Topology in Nanomaterials Research Group
Institute of Technical Physics and Materials Science,
Centre for Energy Research
Eötvös Lóránd Research Network; Hungary

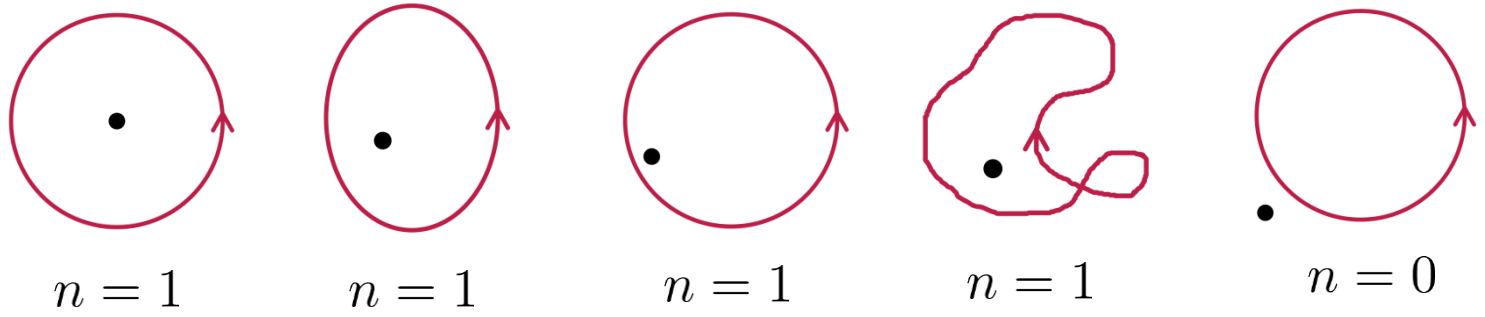
TOPOLOGY OF ELECTRON SYSTEMS

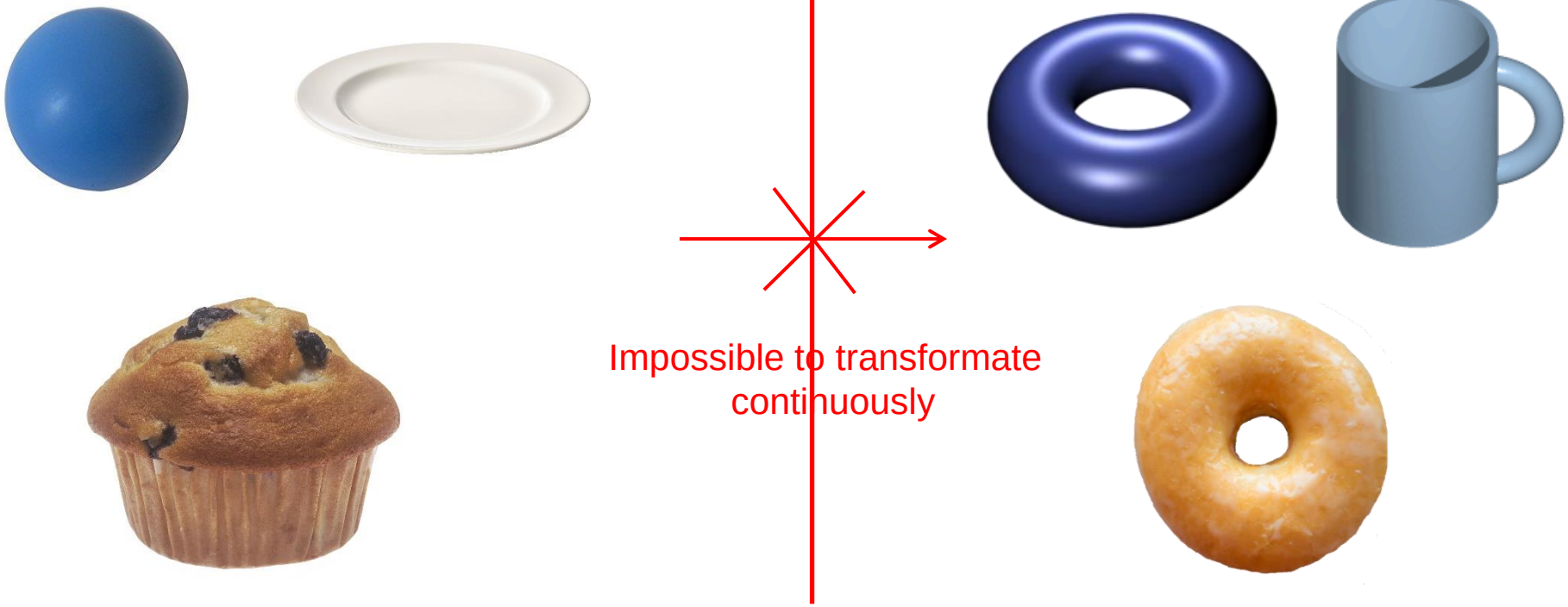
- Topology: the branch of mathematics that deals with the conserved quantities during continuous transformation of geometric objects.
- Gauss-Bonnet relationship on a closed F surface in 3D:

$$\oint \frac{1}{r_1 r_2} dA = 4\pi(1-g)$$

Source: Asbóth, J. K., Oroszlány, L. & Pályi, A. A Short Course on Topological Insulators. Lect. Notes Phys.919, (Springer International Publishing, 2016)

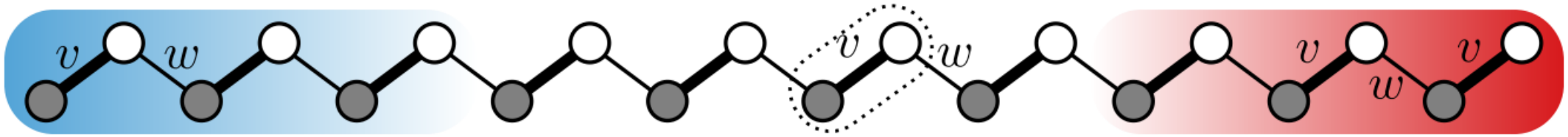
TOPOLOGY OF ELECTRON SYSTEMS





TOPOLOGY OF ELECTRON SYSTEMS: SSH modell

- In Solid State Physics, the electron systems of crystals also have topological properties
- Infinitely long chain model, containing two atoms in the unit cell

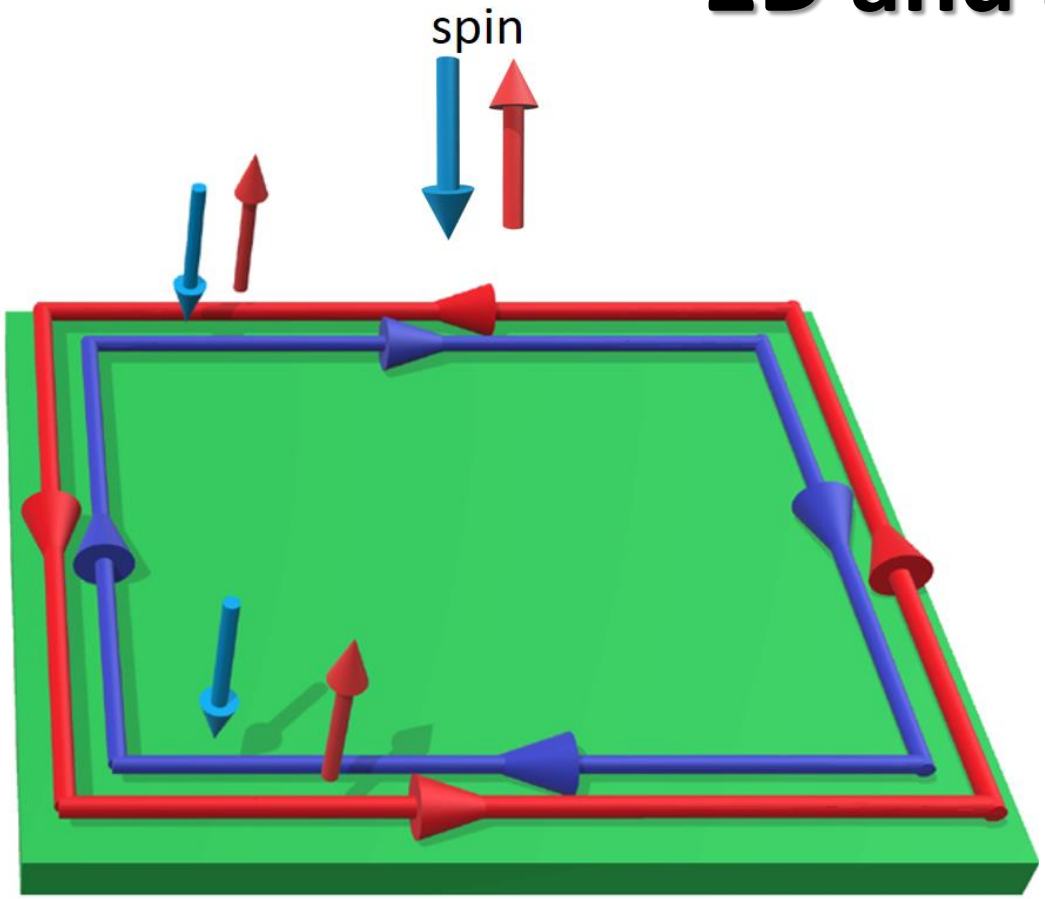


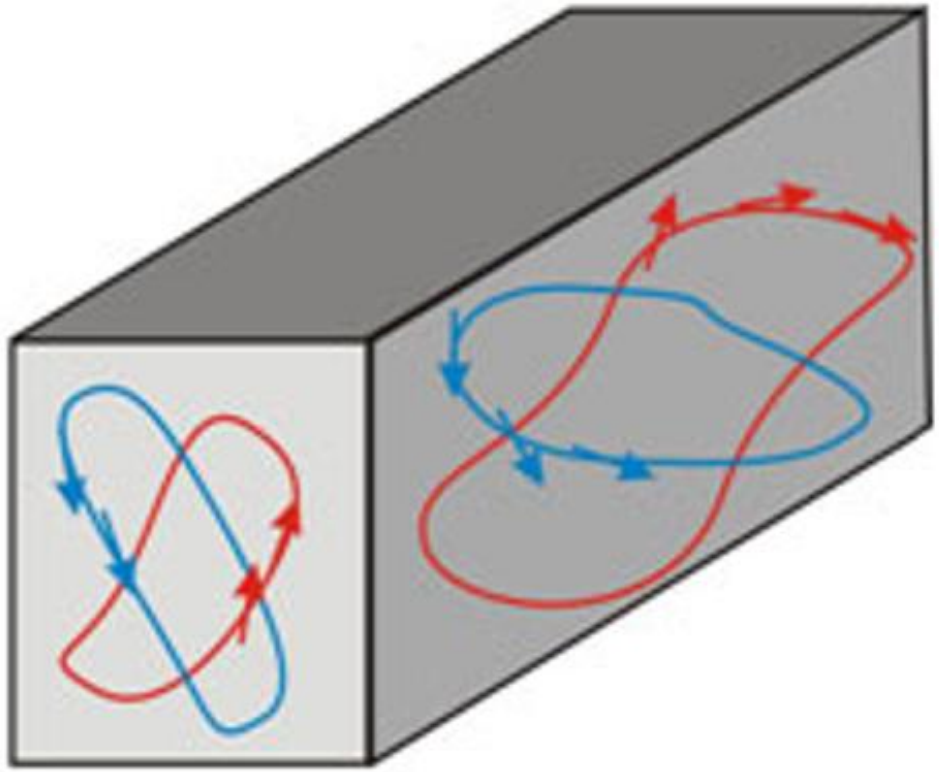
$$\hat{\mathrm{H}} = \mathrm{v}\sum_{\mathrm{m}=1}^{\mathrm{N}}(|\mathrm{m},\mathrm{B}\rangle\langle\mathrm{m},\mathrm{A}| + \mathrm{h.c}) + \mathrm{w}\sum_{\mathrm{m}=1}^{\mathrm{N}-1}(|\mathrm{m}+1,\mathrm{A}\rangle\langle\mathrm{m},\mathrm{B}| + \mathrm{h.c.})$$

- Hamiltonian of the system containing 4 unit cells:

$$\begin{pmatrix} 0 & v & 0 & 0 & 0 & 0 & 0 & 0 \\ v & 0 & w & 0 & 0 & 0 & 0 & 0 \\ 0 & w & 0 & v & 0 & 0 & 0 & 0 \\ 0 & 0 & v & 0 & w & 0 & 0 & 0 \\ 0 & 0 & 0 & w & 0 & v & 0 & 0 \\ 0 & 0 & 0 & 0 & v & 0 & w & 0 \\ 0 & 0 & 0 & 0 & 0 & w & 0 & v \\ 0 & 0 & 0 & 0 & 0 & 0 & v & 0 \end{pmatrix}$$

TOPOLOGY OF ELECTRON SYSTEMS:
2D and 3D cases





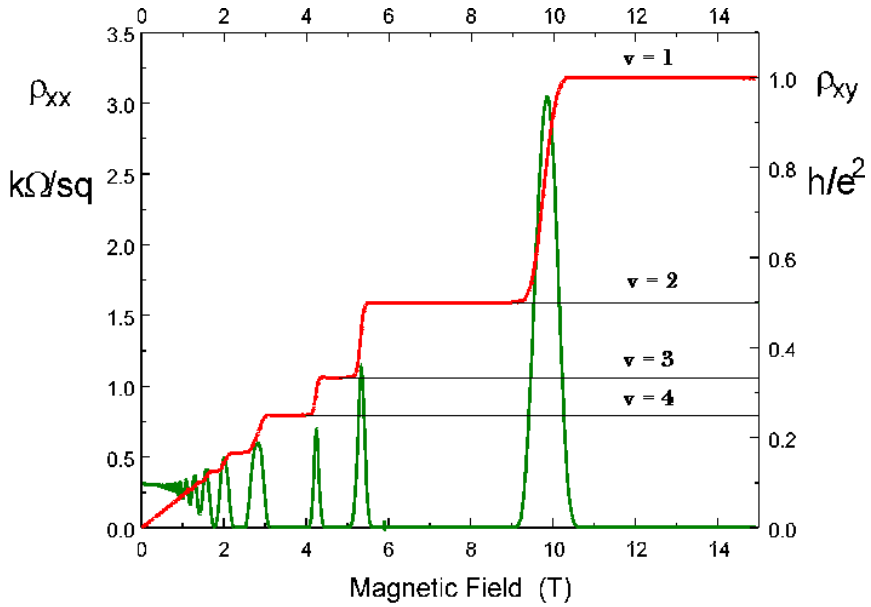
Examples of 2D topological insulators:
WTe_2, CdTe/HgTe, Bi/SiC,

Examples of 3D topological insulators :
Bi2Se3, Bi2Te3,

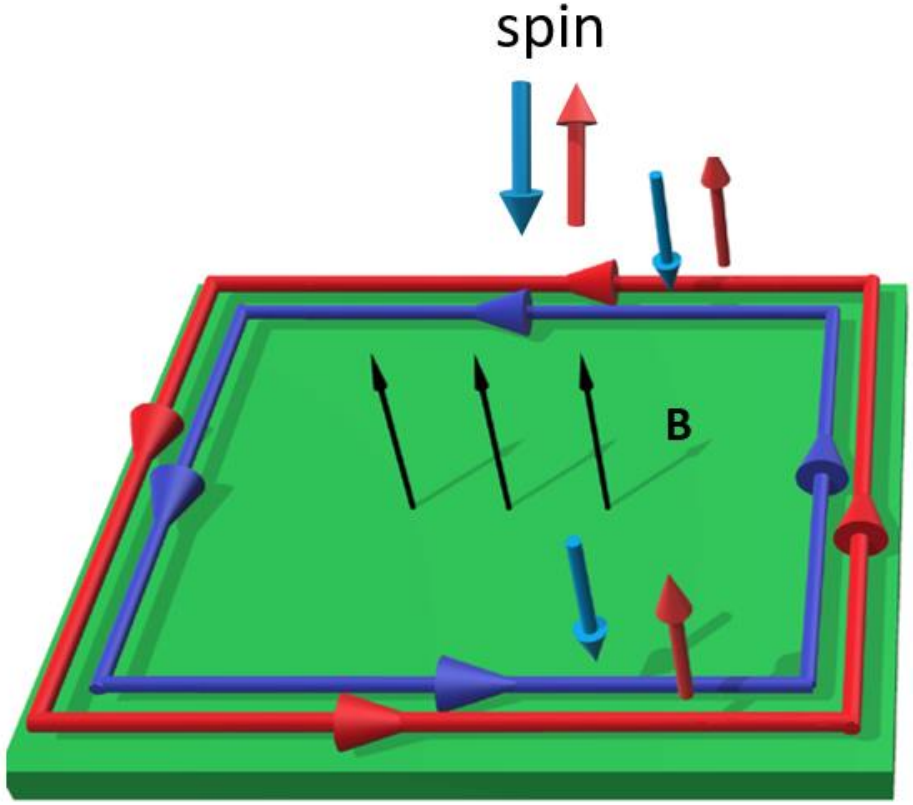
TOPOLOGY OF ELECTRON SYSTEMS: Historical Overview

Quantum Hall effect

- High magnetic field and low temperature required



Source: K. v. Klitzing et al, Phys. Rev. Lett. 45, 494 (1980)

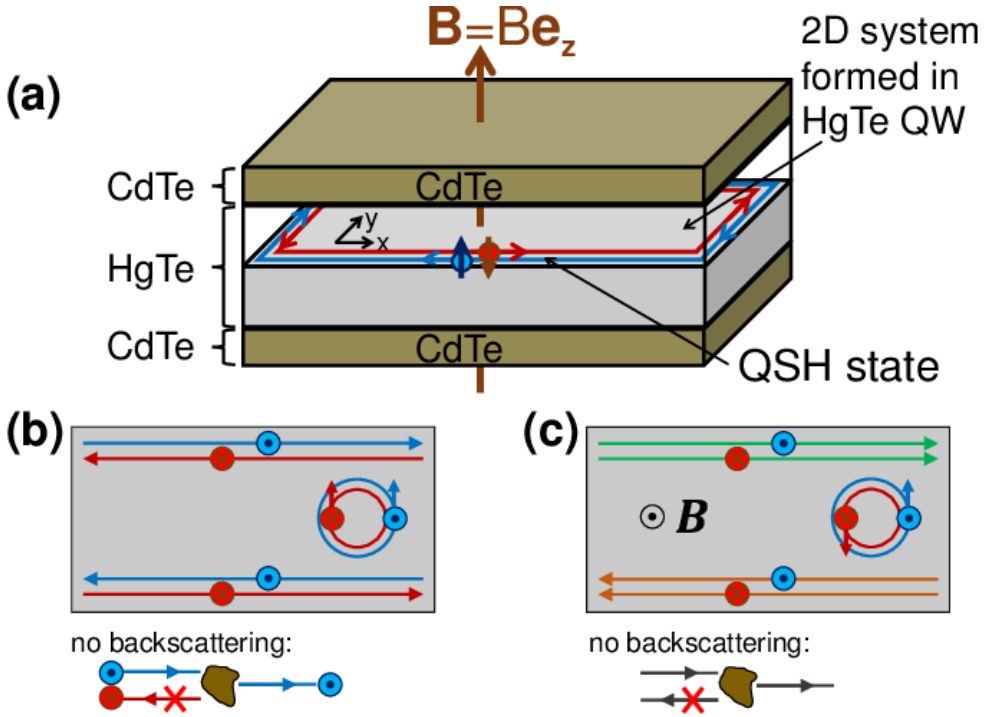


Chern number = 0, 1, 2, 3,…

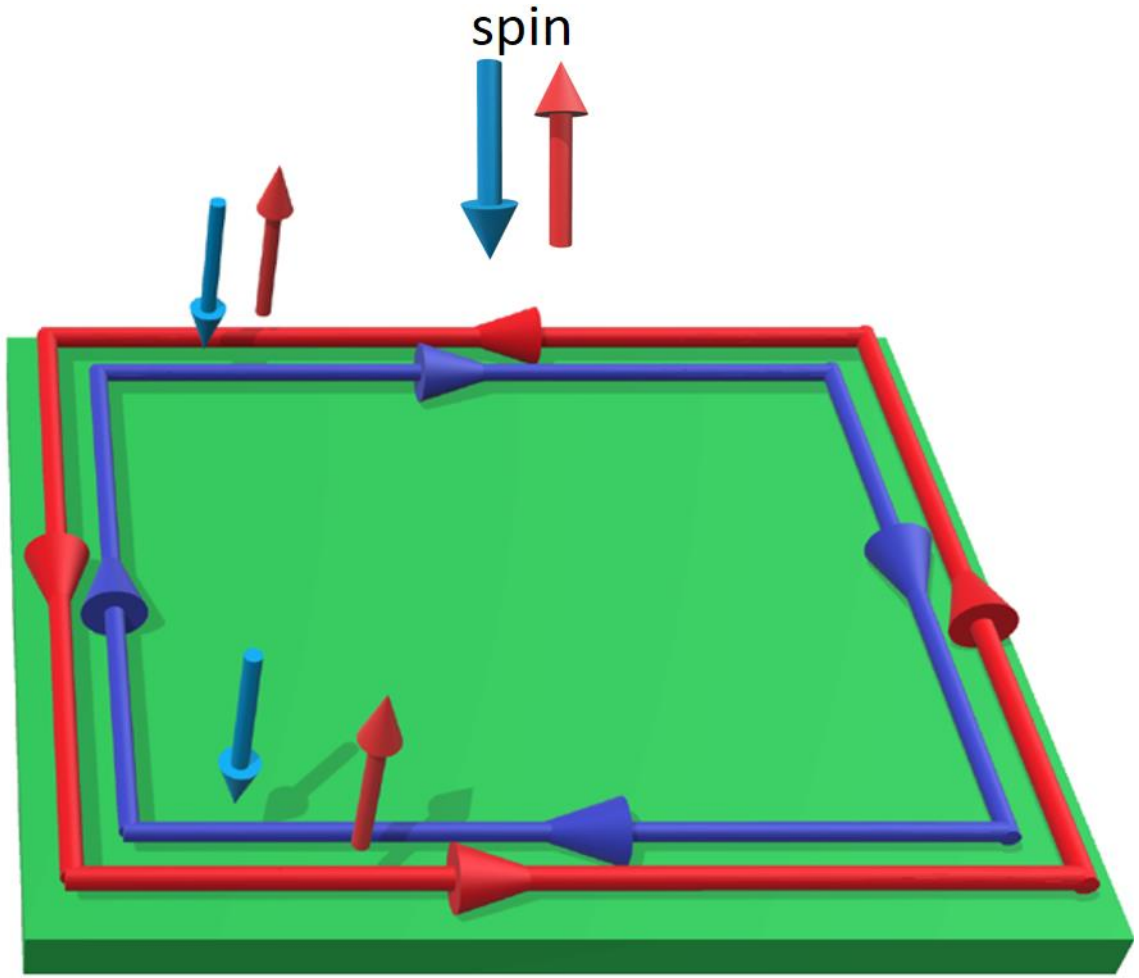
TOPOLOGY OF ELECTRON SYSTEMS: Historical Overview

Quantum spin-Hall effect

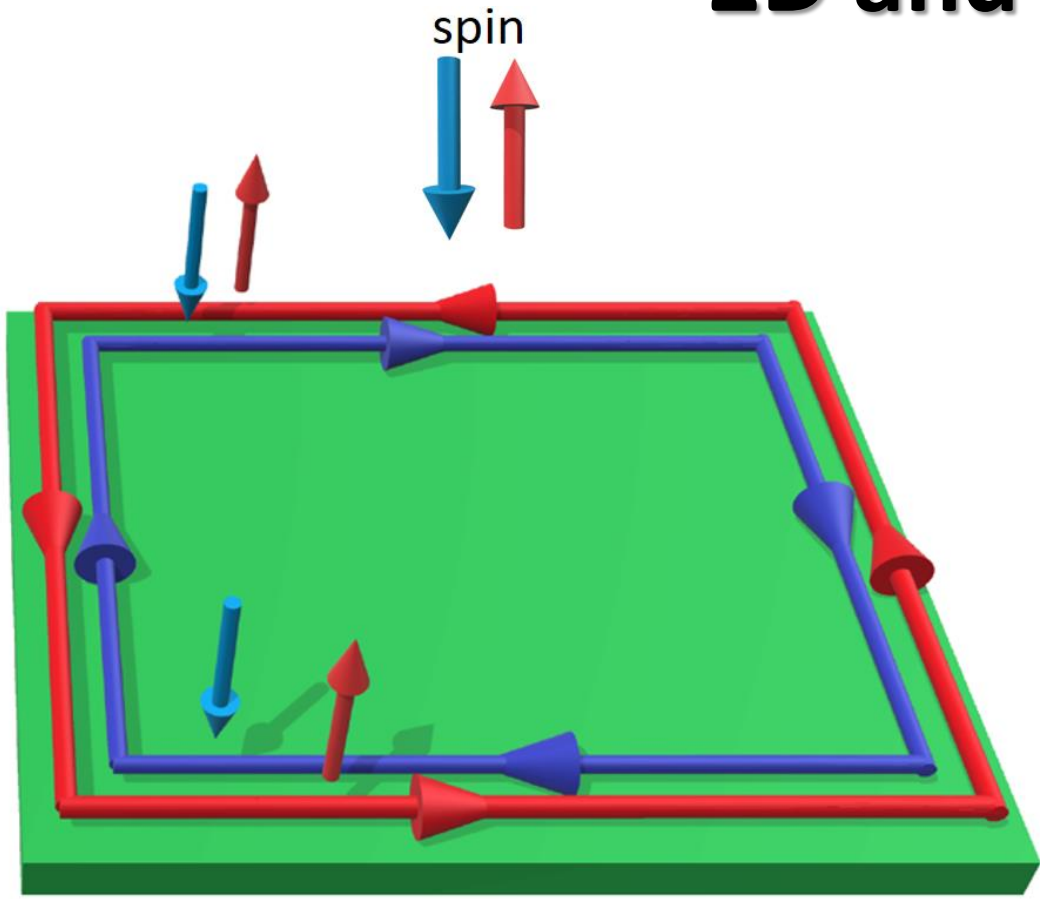
- Low temperature
- HgTe wells



Source: B. Scharf et al, PhysRevB.91.235433 (2015)

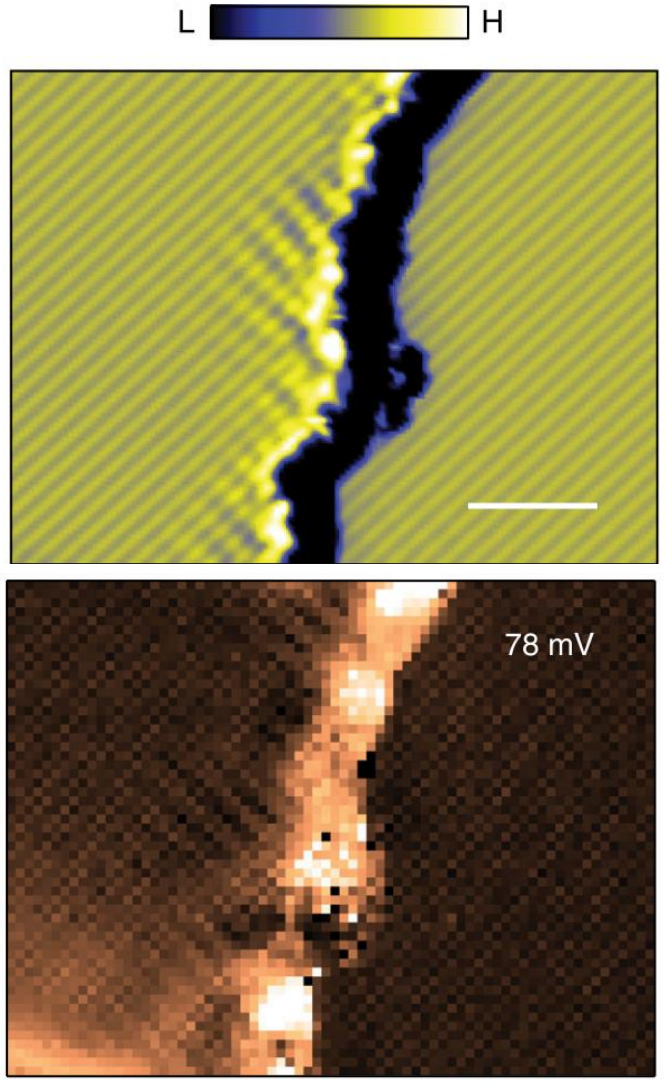


TOPOLOGY OF ELECTRON SYSTEMS: 2D and 3D cases



Examples of 2D topological insulators:
WTe_2, CdTe/HgTe, Bi/SiC,

WTe_2 :

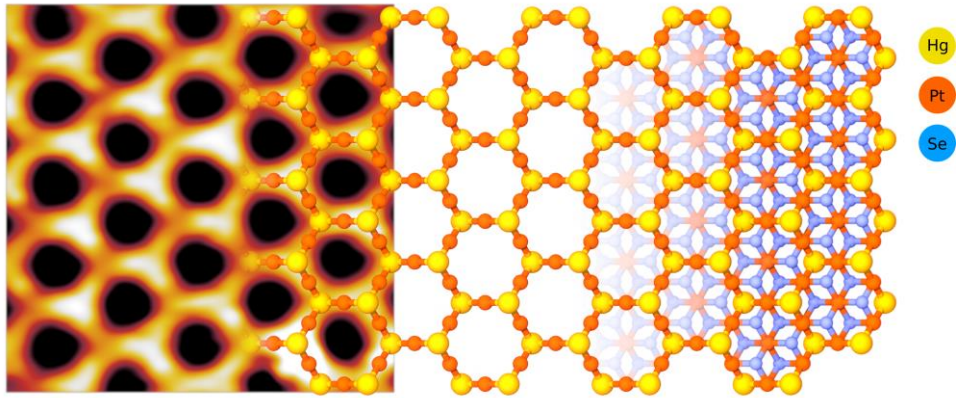


Source
1. Tang, S., et al. Nat. Phys. 13, 683–687 (2017)
2. Peng, L., et al. Nat. Commun. 8, 659 (2017)

A wishlist for 2DTI materials

Looking for:

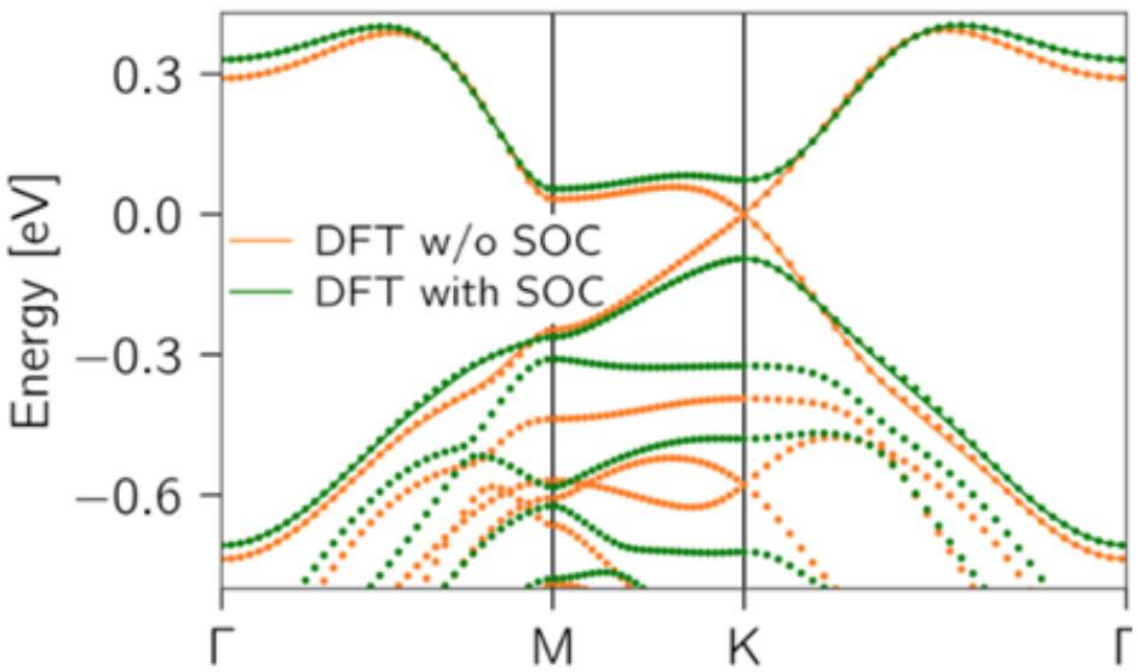
- large gap TI
- possible to exfoliate
- stable under ambient conditions

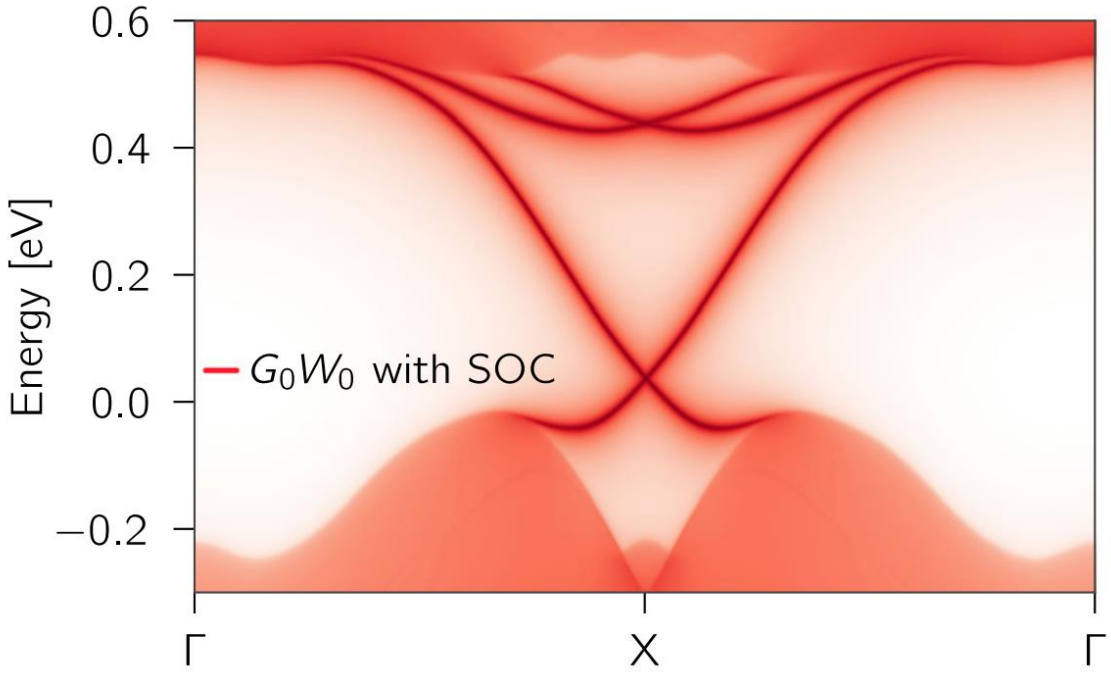


Pt_2HgSe_3

Jacutingaite: Pt_2HgSe_3

- Theoretical calculations predicted that Pt_2HgSe_3 (jacutingaite) is a two dimensional topological insulator

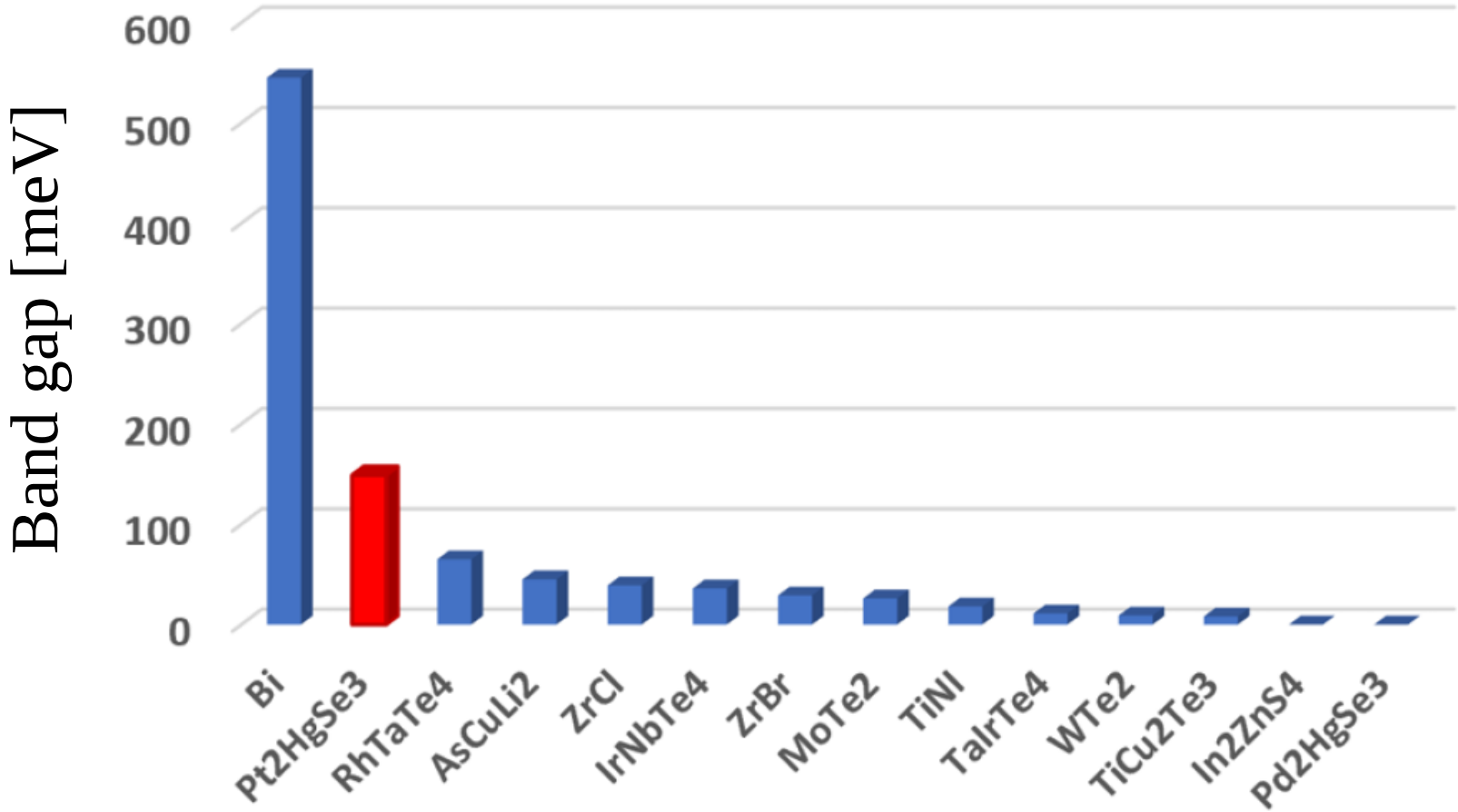




Source: Marrazzo A.: Prediction of a Large-Gap and Switchable Kane-Mele Quantum Spin Hall Insulator. Phys. Rev. Lett. 2018, 120 (11), 117701

Jacutingaite: Pt_2HgSe_3

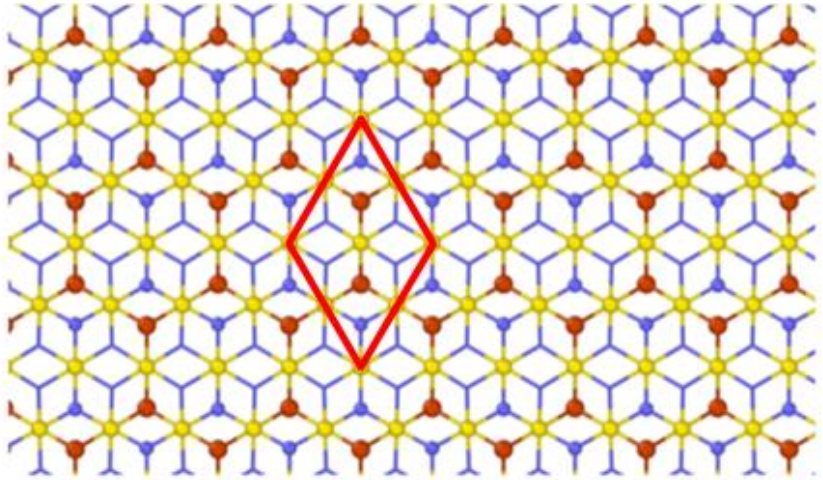
- Several advantages: stable on air, easy to exfoliate and has a high band gap

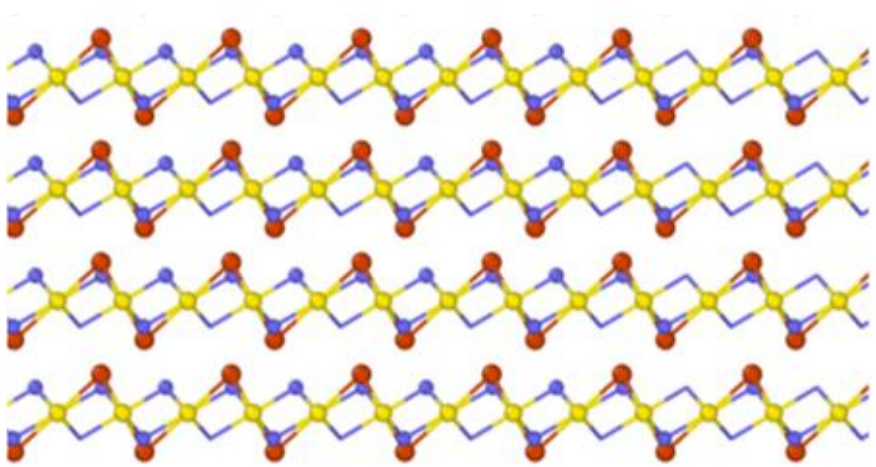


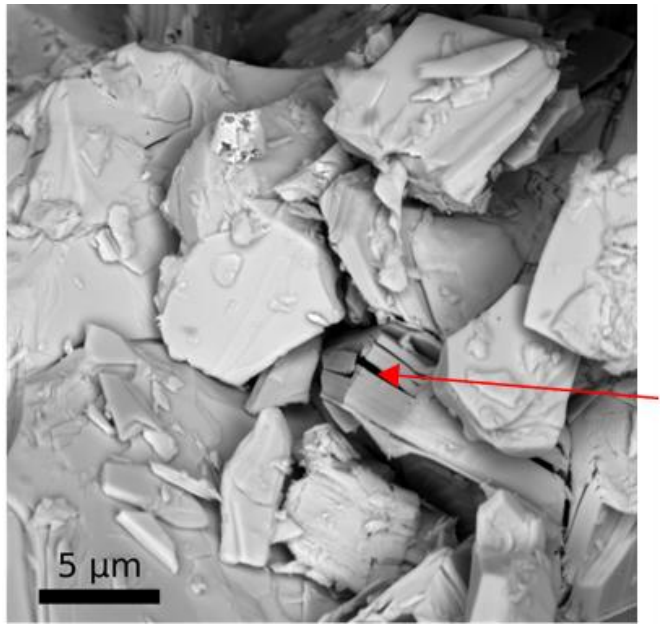
Source: https://www.materialscloud.org/discover/2dtopo/dashboard/plot

Jacutingaite: Pt_2HgSe_3

- The states around the band gap are located on the honeycomb lattice formed by the Pt and Hg atoms



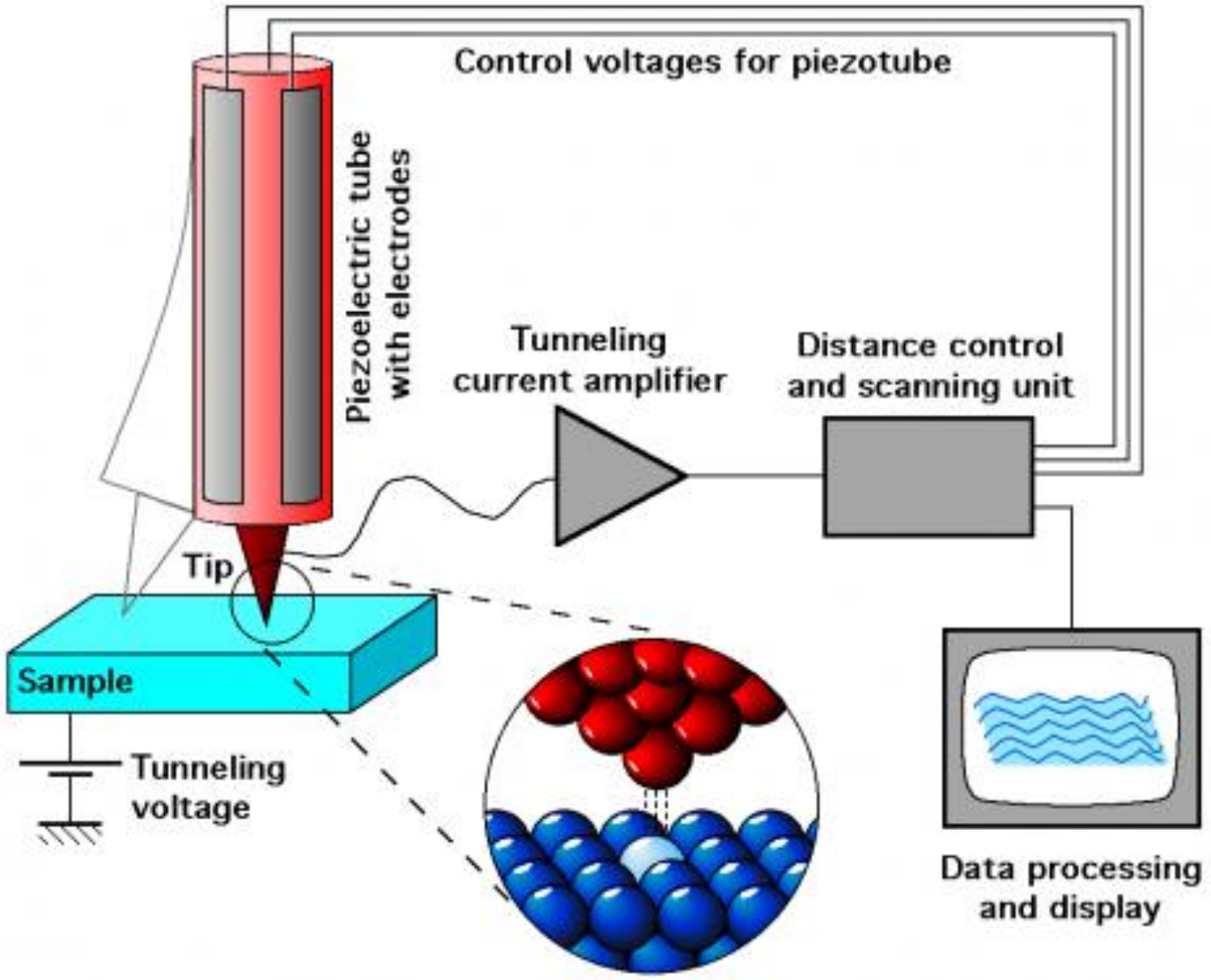




We were the first to study:

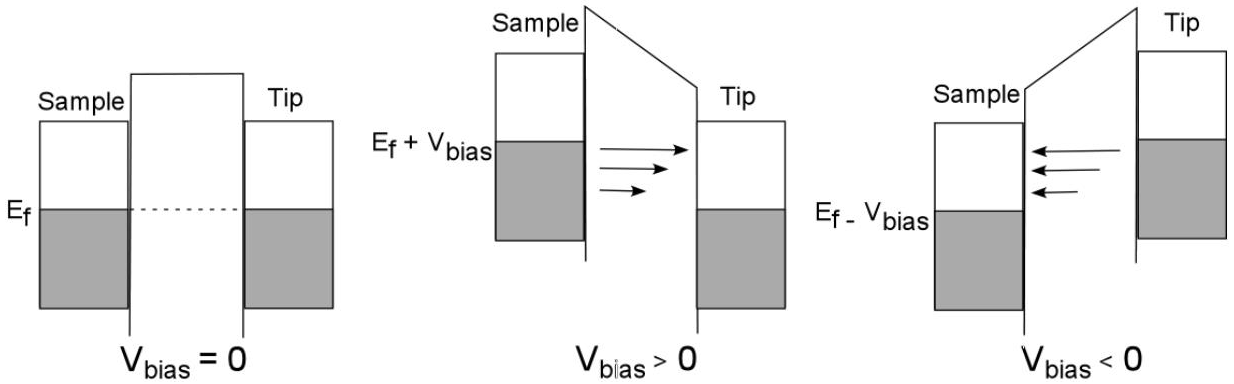
- The exfoliation of Pt_2HgSe_3
- Raman spectrum of Jacutingaite
- The density of states with atomic resolution

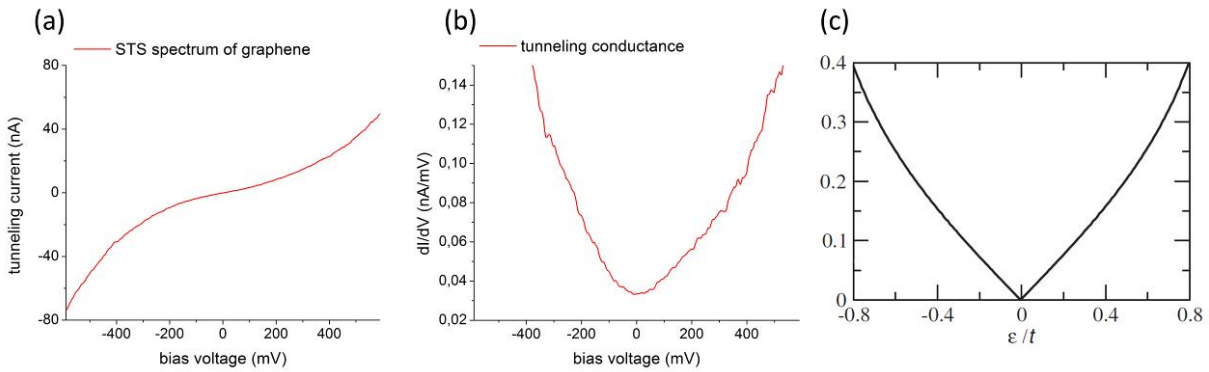
STM: Scanning Tunneling Microscopy



Source: Roland Wiesendanger: Scanning Probe Microscopy and Spectroscopy: Methods and Applications, Cambridge University Press, Sep 29, 1994

STM: Scanning Tunneling Microscopy





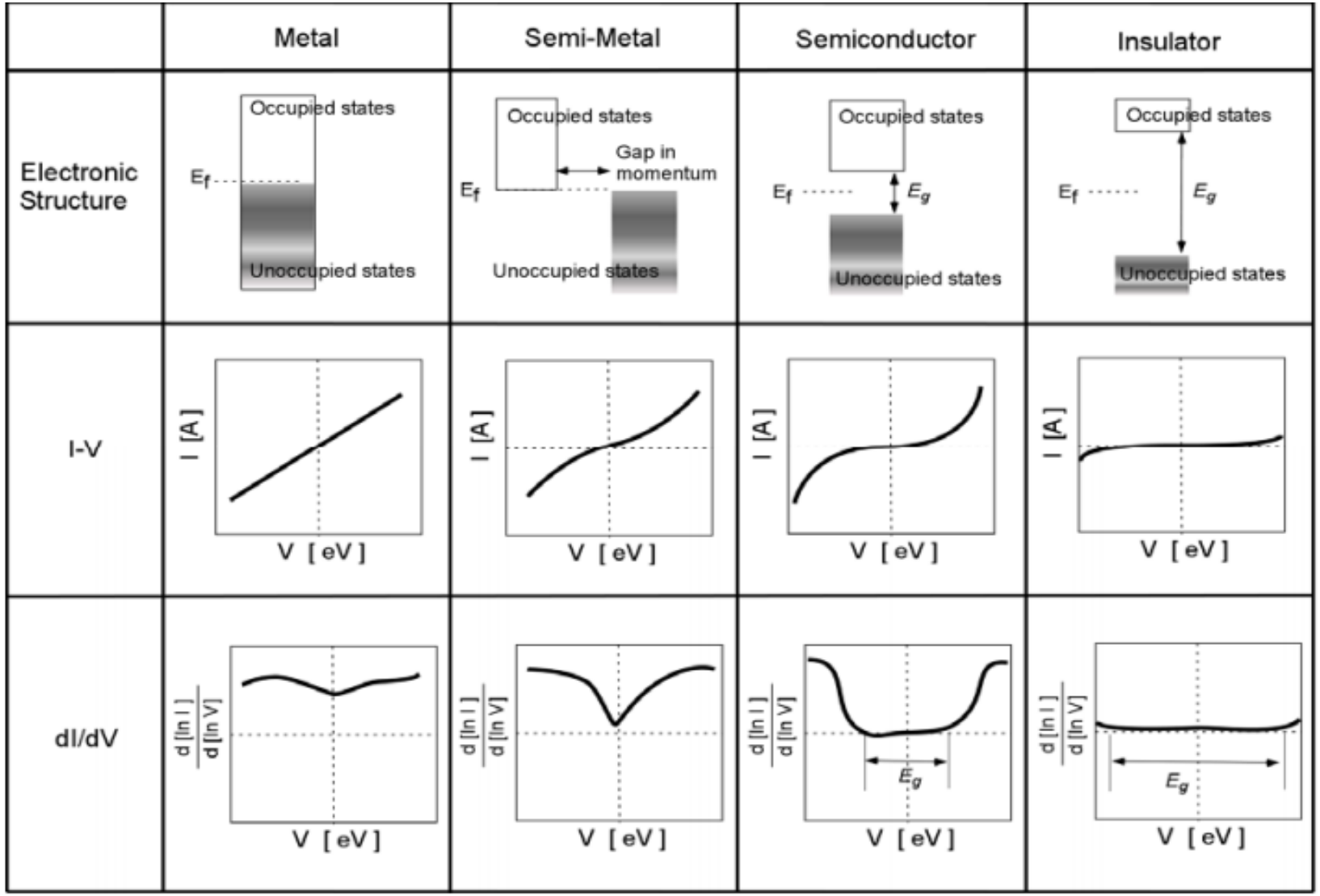
Source: Roland Wiesendanger: Scanning Probe Microscopy and Spectroscopy: Methods and Applications, Cambridge University Press, Sep 29, 1994

$$I = 4\pi e\hbar^{-1} \int_{-\infty}^{\infty} \rho_{tip}(E - eV)\rho_{sample}(E)\,[f(E - eV) - f(E)]\,|\,M\,|^2\,dE$$

$$I \cong V_{bias}\,\rho_{sample}(E_f)\exp\left[-\frac{2\left(\sqrt{2m(\varphi - E)}z\right)}{\hbar}\right] \cong V_{bias}\,\rho_{sample}\,\exp\left(-1.025\sqrt{\varphi}z\right)$$

Source: G. Binnig, H. Rohrer, C. Gerber, E. Weibel, Surface studies by scanning tunneling microscopy. Phys. Rev. Lett. 49, 57–61 (1982)

STM: Scanning Tunneling Microscopy

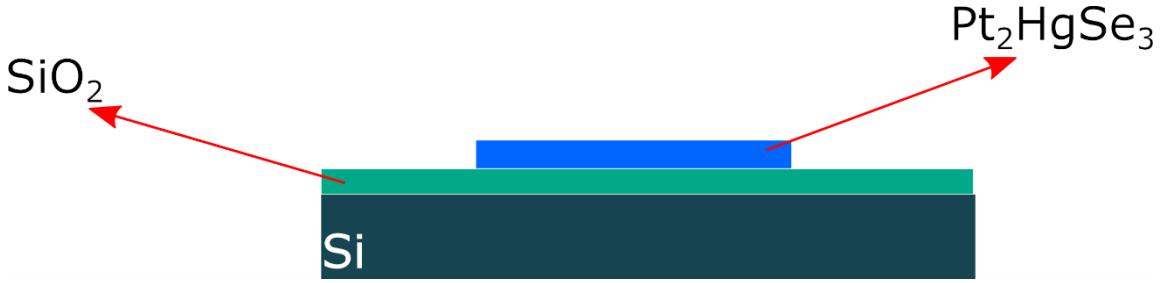


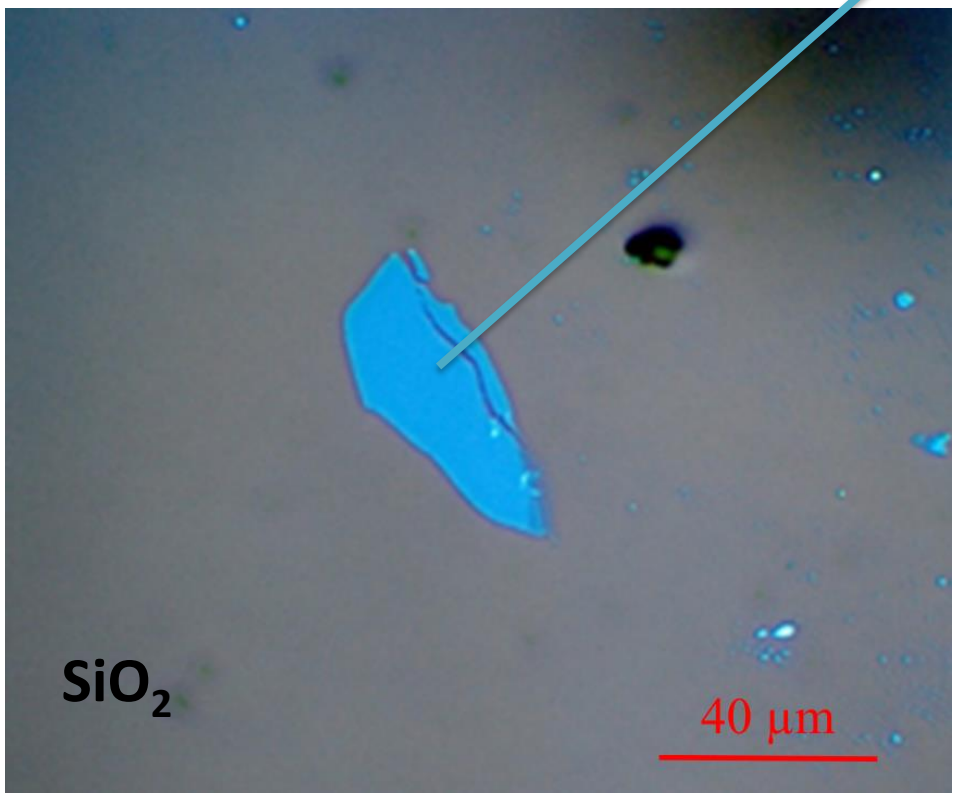
Source: G. Binnig, H. Rohrer, C. Gerber, E. Weibel, Surface studies by scanning tunneling microscopy. Phys. Rev. Lett. 49, 57–61 (1982)

Personal results

Preparation of samples: Mechanical exfoliation

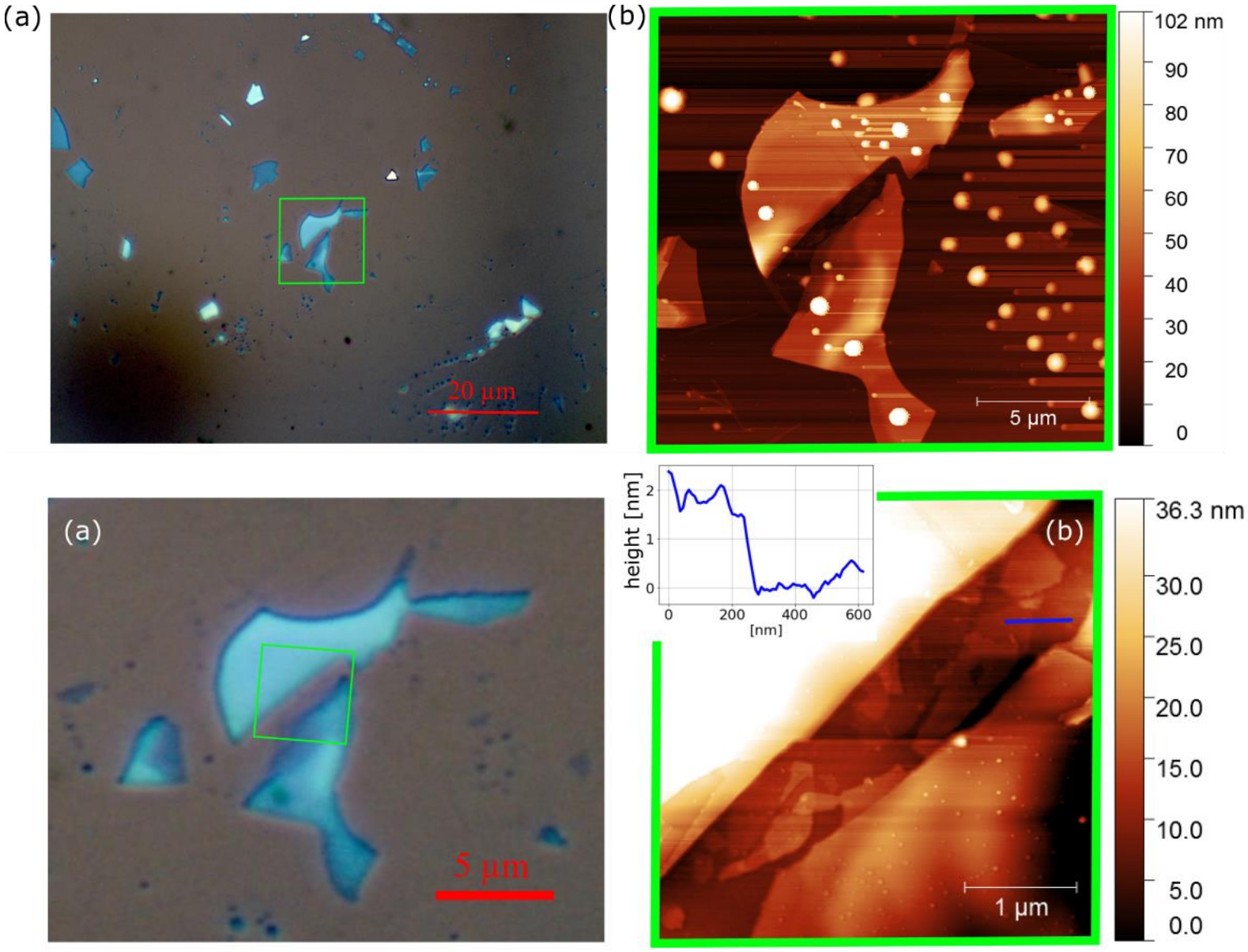
Optical microscopy analysis:





Personal results

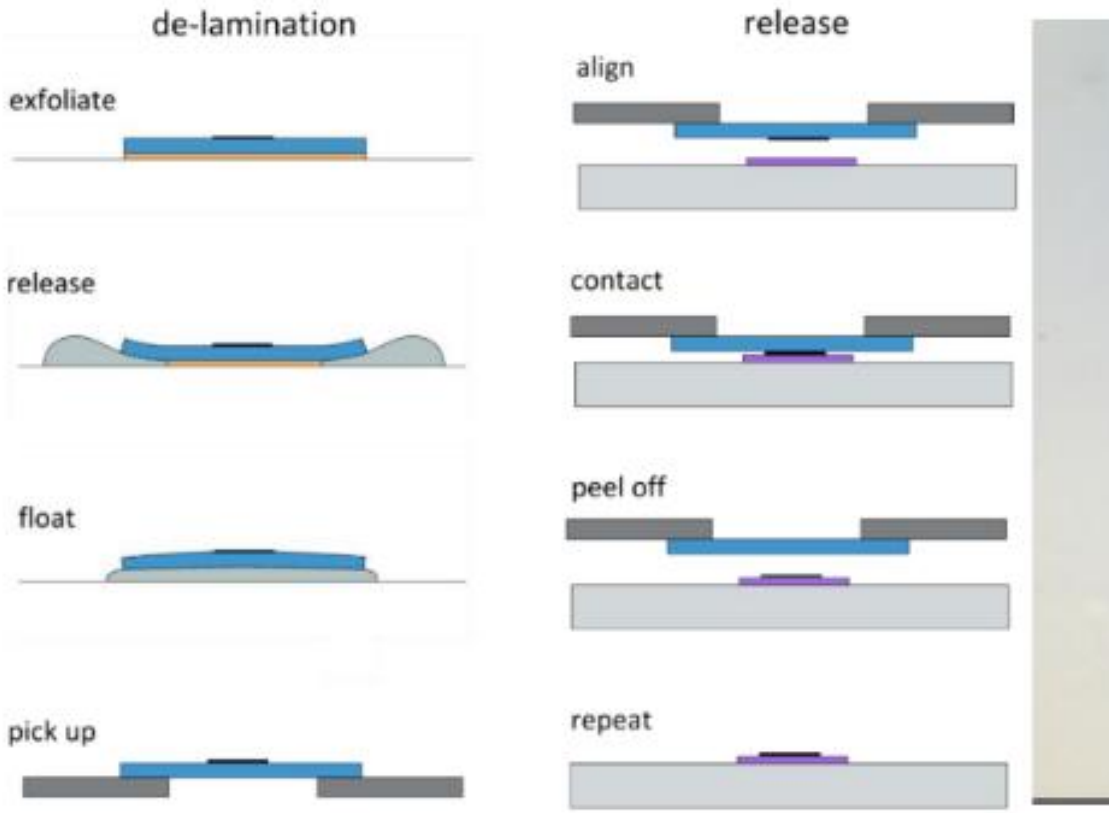
AFM measurements:

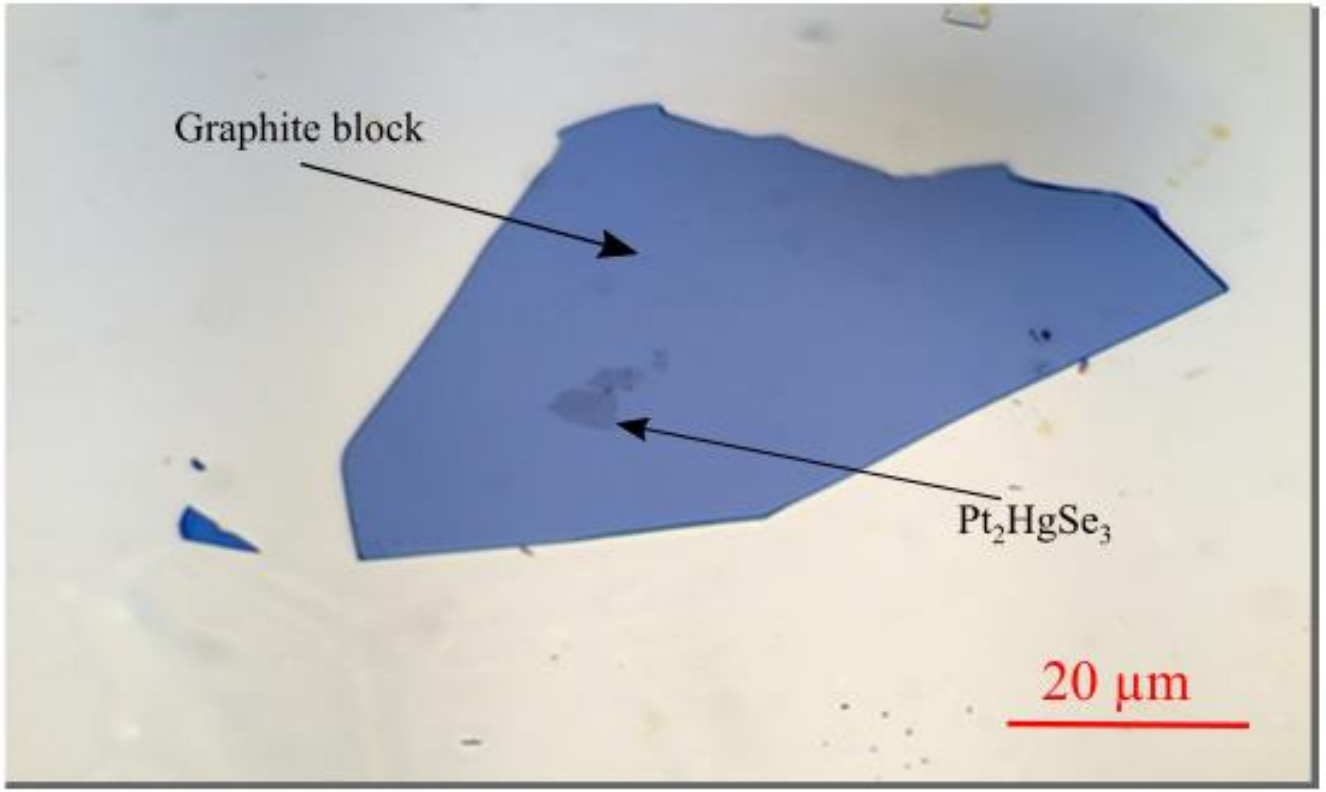


Personal results

Transferring the thin crystal layers

- The goal: realization of heterostructures with other materials
- The method:

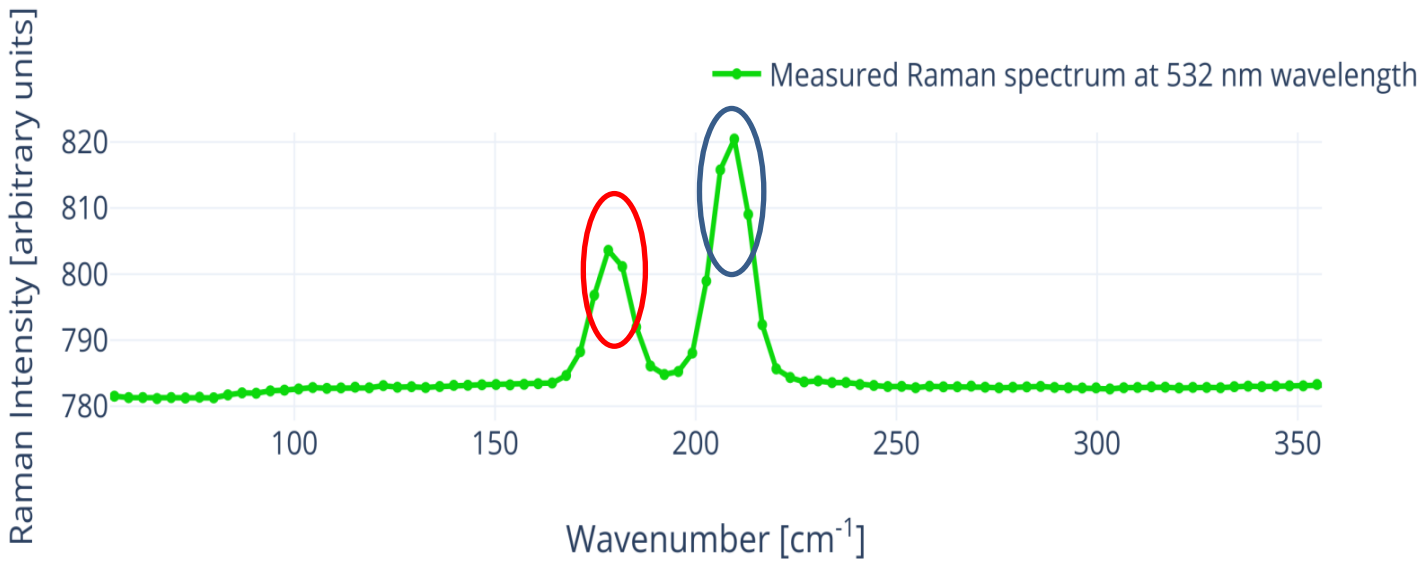


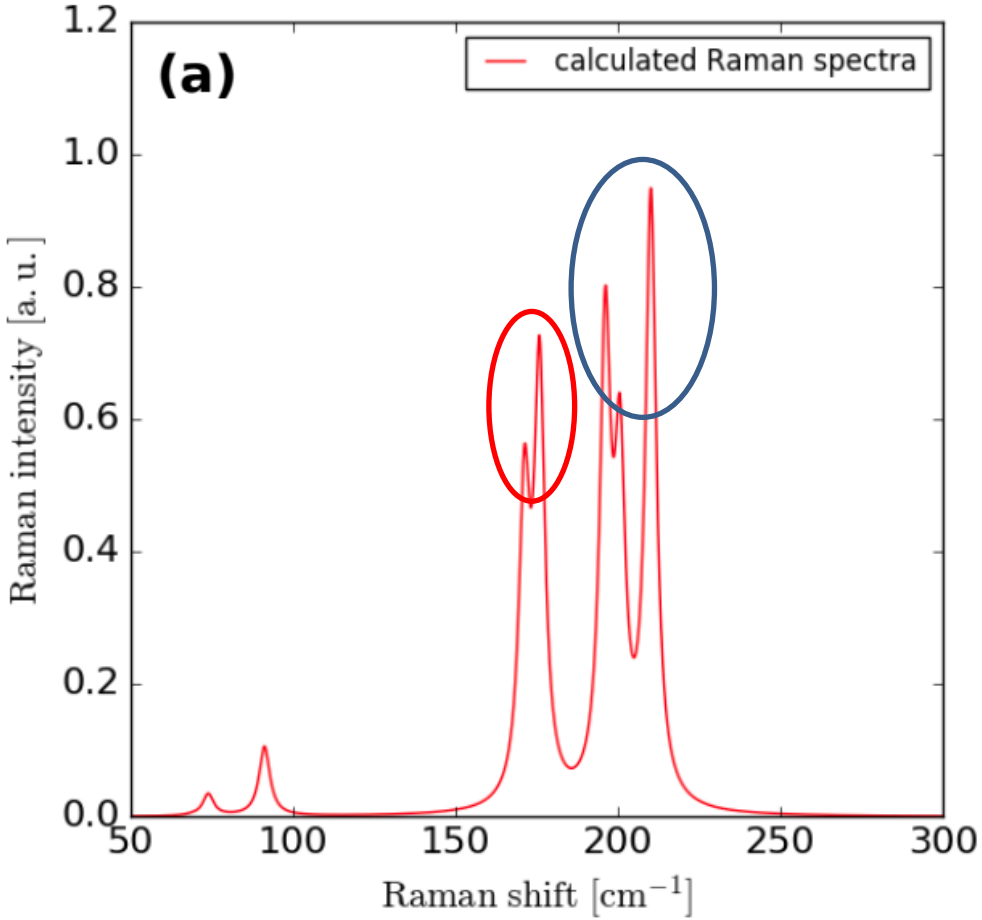


Source: A. V. Kretinin et al: Electronic properties of graphene encapsulated with different 2D atomic crystals, Nano Lett. 2014, 14, 6, 3270–3276

Personal results

CONFOCAL RAMAN SPECTROSCOPY

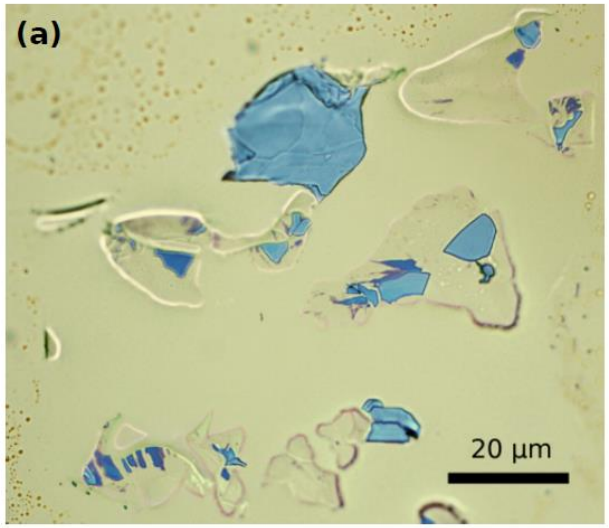


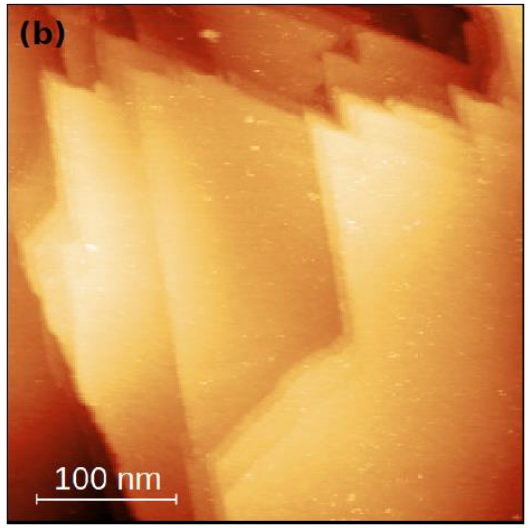


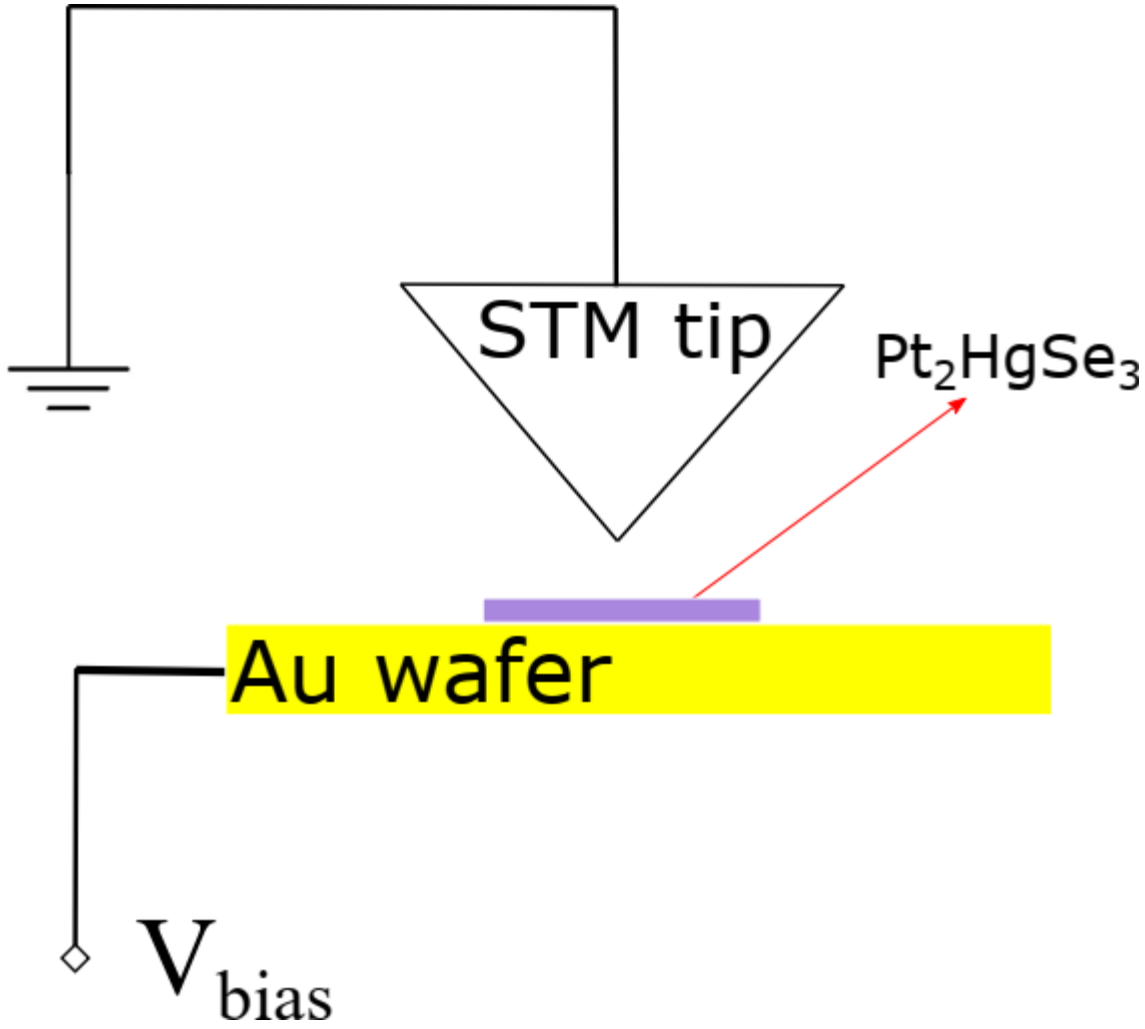
Source: Kandrai K. et al: Signature of Large-Gap Quantum Spin Hall State in the Layered Mineral Jacutingaite, Nano Lett. 2020, 20, 7, 5207–5213

Personal results

STM measurements

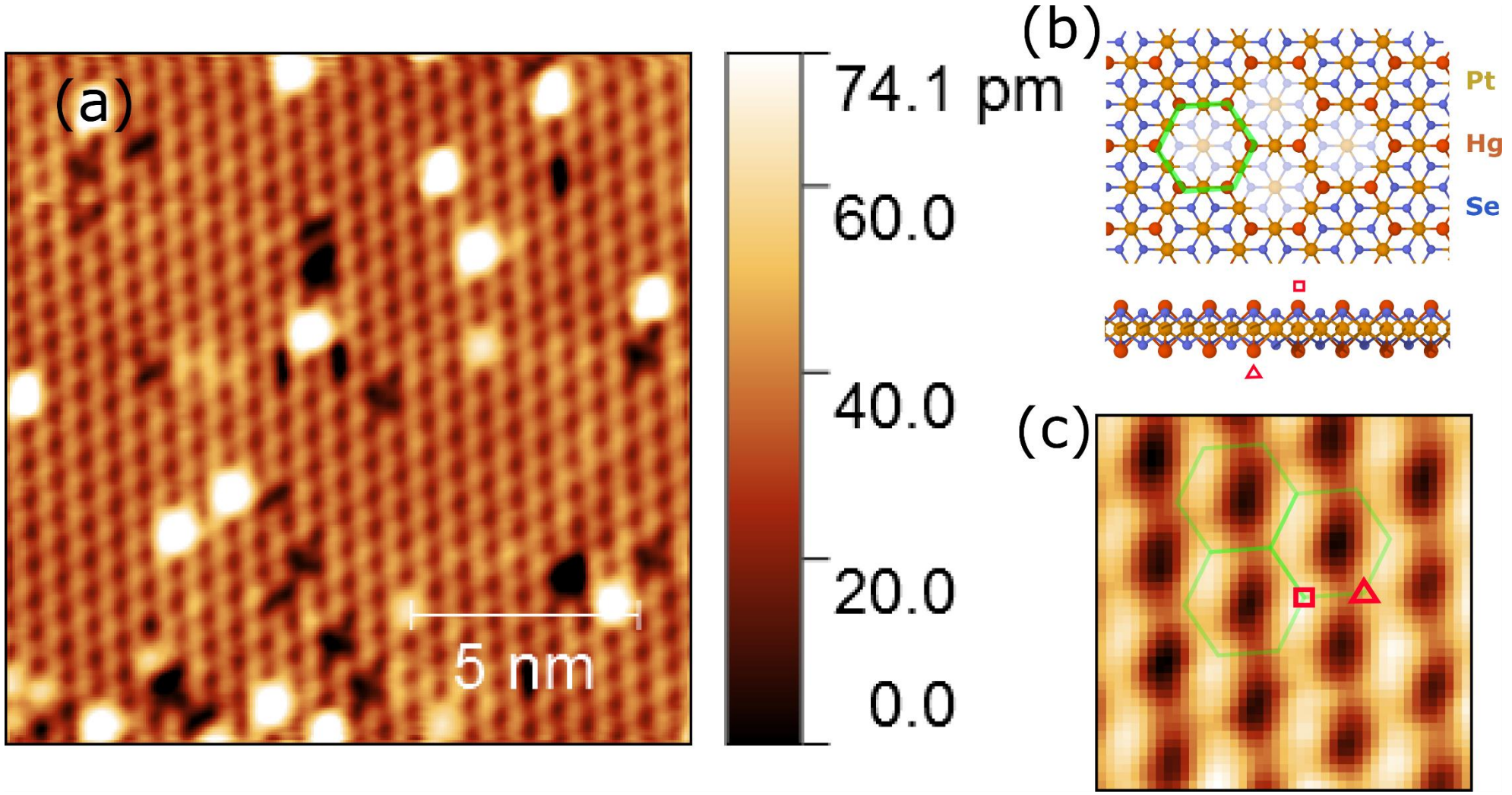






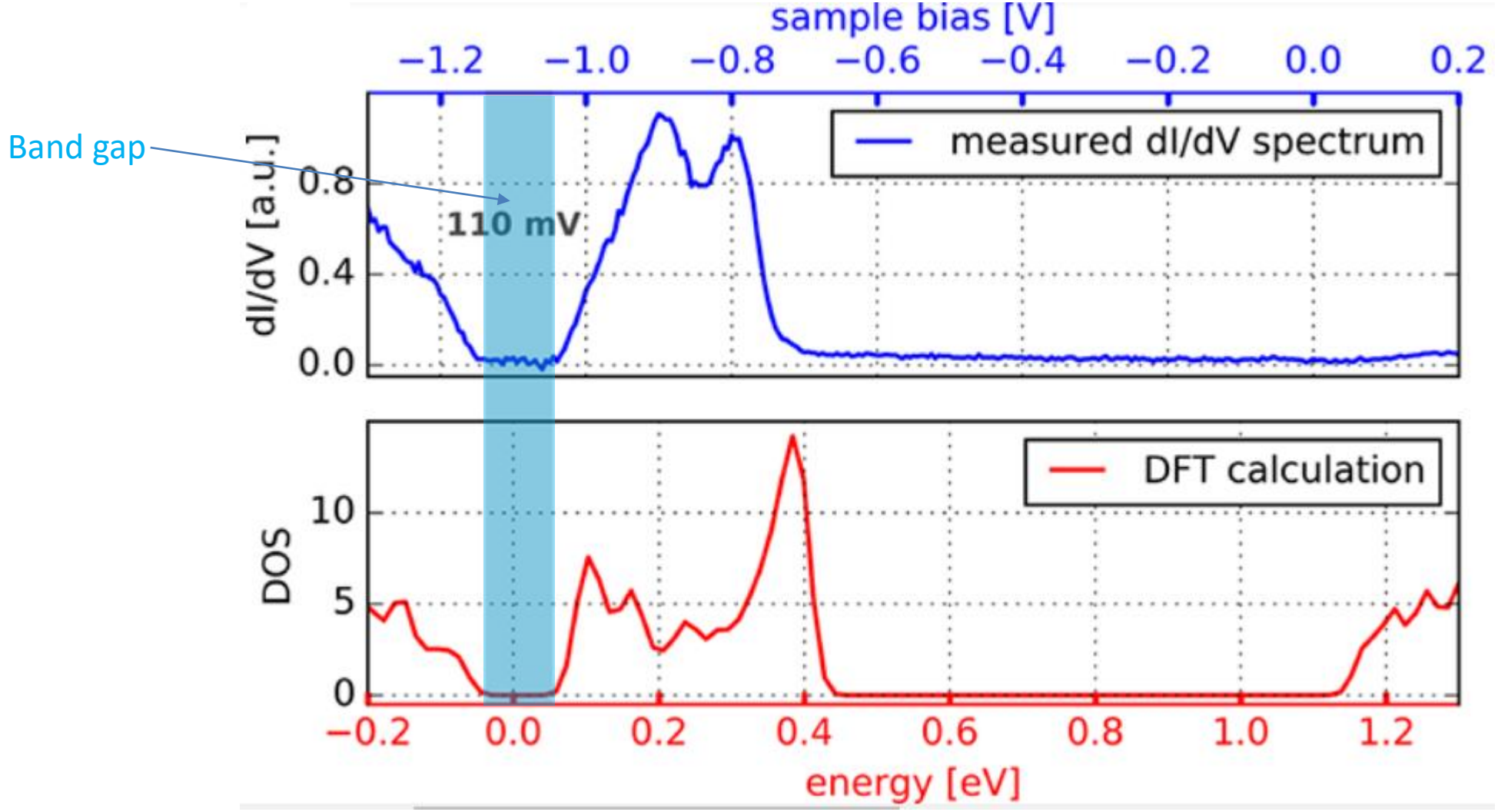
Personal results

STM measurements



Personal results

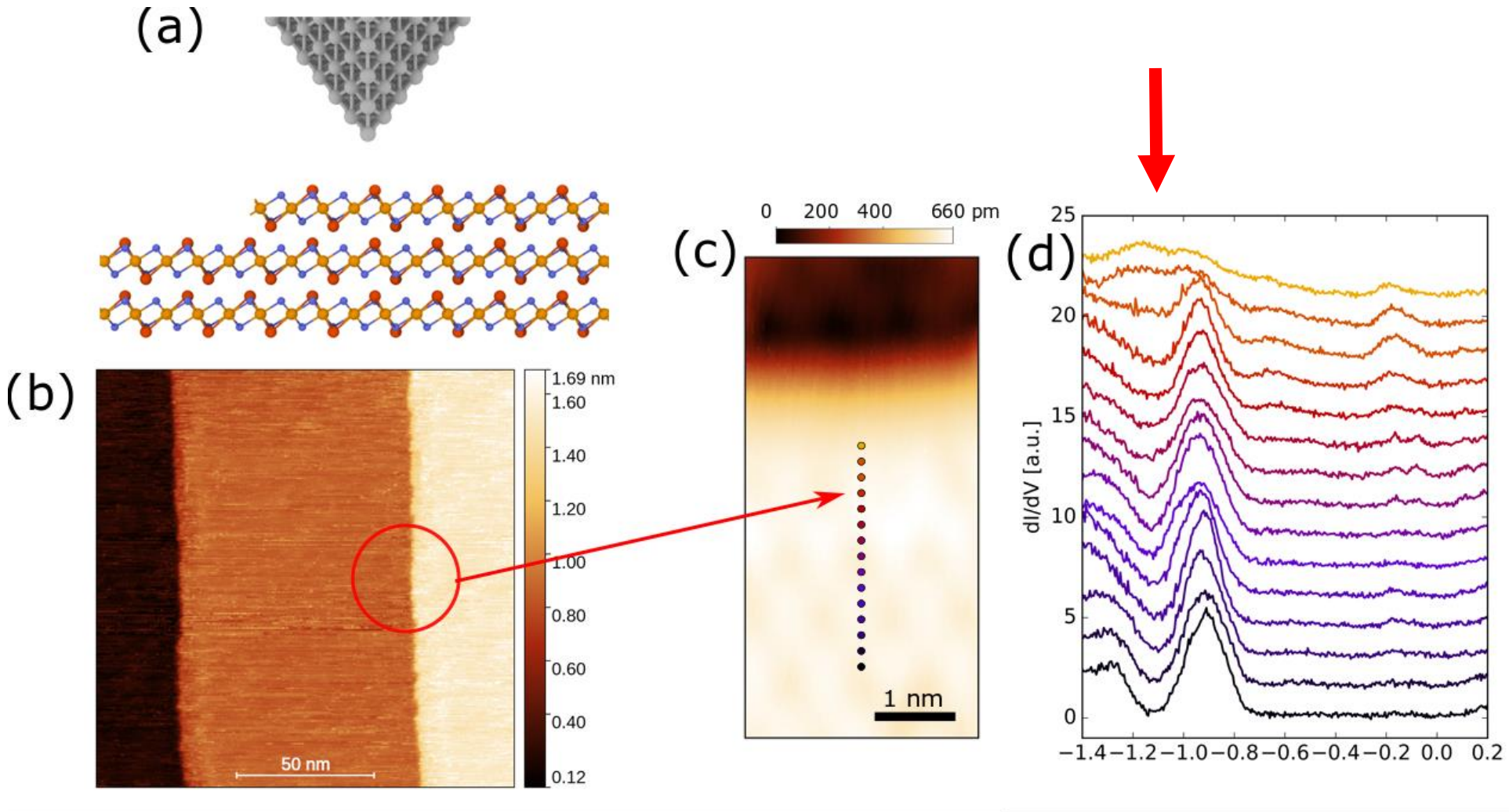
STM measurements



Source: Kandrai K. et al: Signature of Large-Gap Quantum Spin Hall State in the Layered Mineral Jacutingaite, Nano Lett. 2020, 20, 7, 5207–5213

Personal results

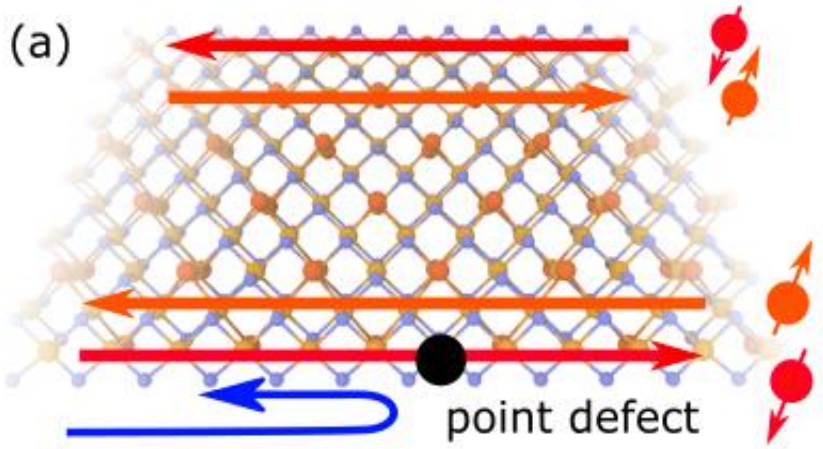
STM measurements

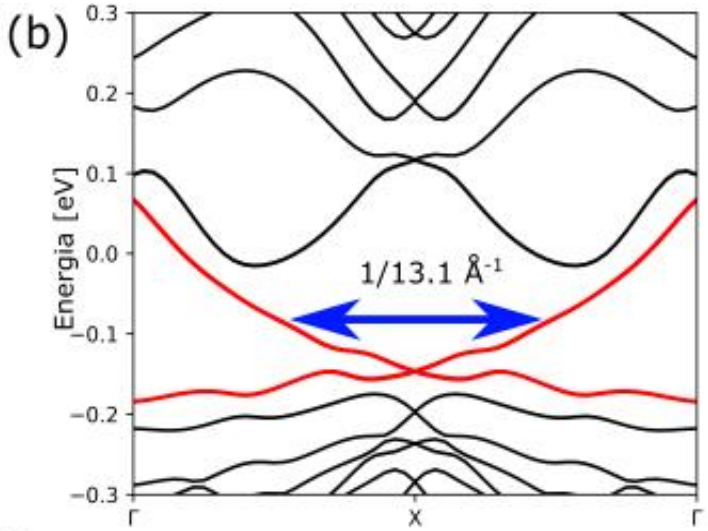


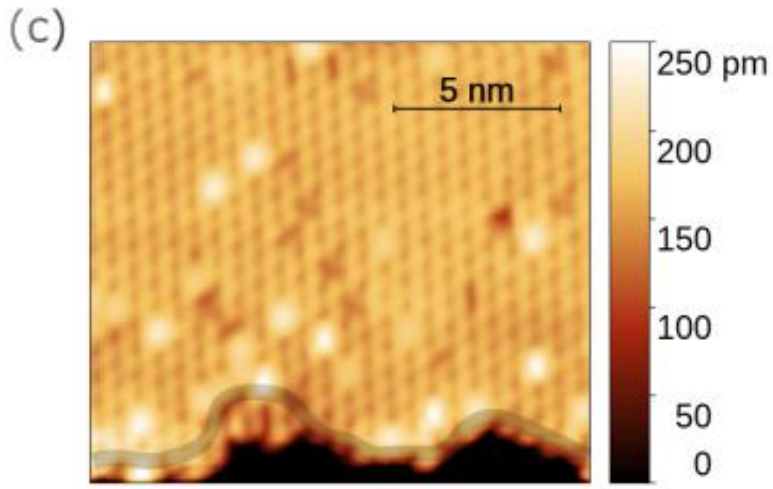
PERSONAL RESULTS

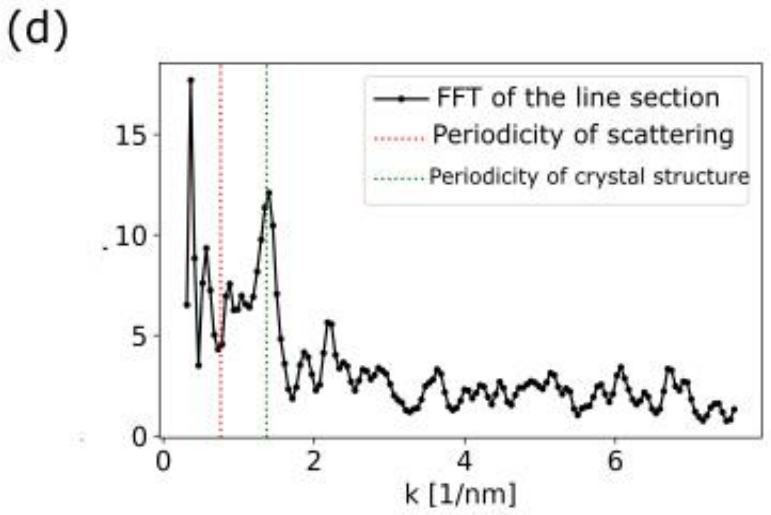
STM measurements

- Further measurements





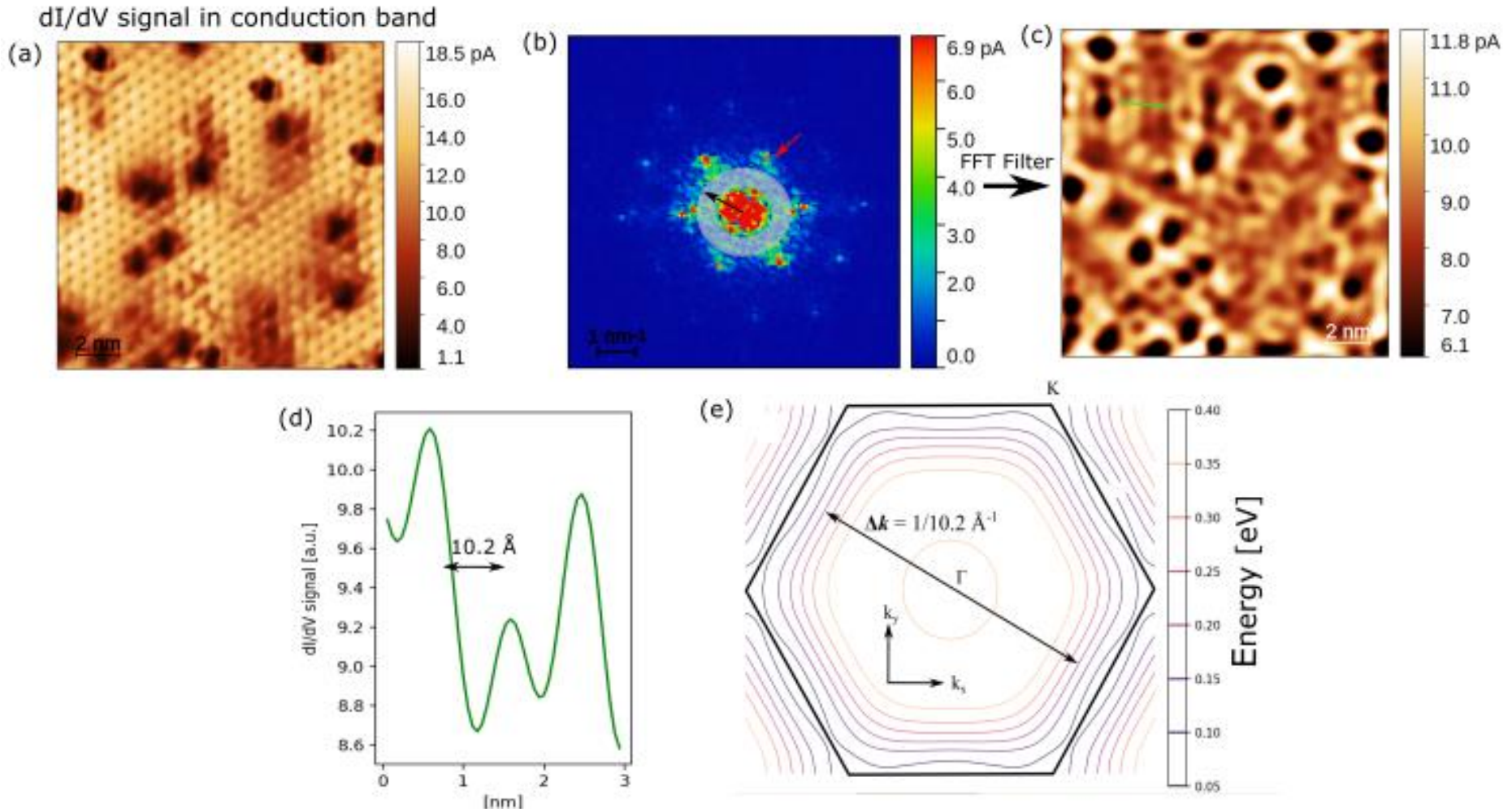




PERSONAL RESULTS

STM measurements

- Further measurements



Conclusions

- I was the first to exfoliate and to realize 3 layer thick Pt_2HgSe_3-t.
- I was the first to measure the Raman spectrum of the material.
- I was the first to perform STM measurements, by this showing the band gap and the electronic states around the edges.
- As a continuation of my work, my colleagues from Budapest performed DFT calculation and further STM measurements to prove the topological nature of the edge states.

Thank you for your attention!