M U N I

COMMENTARY TO HABILITATION THESIS[1]

Thin films of topological insulators

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Topological insulators are materials with unique electronic structure of surface states. The bulk electronic structure of the topological insulators is topologically non-trivial. The boundary between topologically trivial and non-trivial material hosts surface (interface) states with Dirac cone-like dispersion. The bulk states have an ordinary band gap; thus, the volume electronic properties are identical to an ordinary insulator or semiconductor. In an ordinary insulator or semiconductor, the surface states are susceptible to particular surface morphology, impurities, and other defects. The typical surface states are usually localized at surface defects and cannot serve as a transport channel in a device. On the contrary, the interface between topologically non-trivial and trivial material has unique boundary states with linear dispersion, which are robust against boundary shape or impurities. Thus they are called topologically protected, and electric transport via boundary states has interesting quantum properties.

The thesis deals with the work performed with topological insulators thin films. In collaboration with co-workers, we started the growth and characterization of the topological insulators relatively soon after their discovery in 2011. Our research at first focused on topological insulator thin film growth optimization and physical properties of bismuth chalcogenide thin films.

Later we started to include magnetic doping with manganese since ferromagnetic topological insulators have unusual physical properties such as quantum anomalous Hall effect. We have published one of the early works showing high-quality epitaxial thin films of bismuth telluride [1] and structural properties of natural heterostructures combining Bi2Te3 and Bi2 layers [2].

Our most significant results were achieved with ferromagnetic topological insulators. Our paper has demonstrated for the first time the direct observation of band gap opening in topological surface states due to ferromagnetic order in $Bi_2Te_3/MnBi_2Te_4$ heterostructures [6]. Later we have shown a high ferromagnetic ordering temperature of 50 K in $MnSb_2Te_4$ topological insulator [7].

Last but not least, we have also worked with topological crystalline insulator layers. We have demonstrated a phase transition from a topological crystalline insulator to a strong topological insulator by doping-induced symmetry breaking [8]. The author’s contribution was mainly in the structural characterization of the prepared films using XRD and later HRTEM, but also to band structure measurements at synchrotron sources, and x-ray absorption spectroscopy.

The first part of the thesis briefly introduces the topological insulator theory and physical properties of selected topological insulator materials. The second chapter presents

[1] The commentary must correspond to standard expectations in the field and must include a brief characteristic of the investigated matter, objectives of the work, employed methodologies, obtained results and, in case of co-authored works, a passage characterising the applicant’s contribution in terms of both quality and content.

experimental methods used in the thesis by the author. Special attention is devoted to x-ray scattering methods as a primary specialization. The last part of the thesis includes a series of research papers.

[1] Growth, Structure, and Electronic Properties of Epitaxial Bismuth Telluride Topological Insulator Films on BaF_2 (111) Substrates, O. Caha, A. Dubroka, J. Humlíček, V. Holý, H. Steiner, M. Ul-Hassan, J. Sánchez-Barriga, O. Rader, T. N. Stanislavchuk, A. A. Sirenko, G. Bauer, and G. Springholz, Crystal Growth and Design 13, 3365 (2013).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
40	35	45	25

Author's contribution: XRD experiment and analysis, transport and thermoelectric experiment, manuscript writing.

[2] Structure and composition of bismuth telluride topological insulators grown by molecular beam epitaxy, H. Steiner, V. Volobuev, O. Caha, G. Bauer, G. Springholz, and V. Holý, J. Appl. Crystallography 47, 1889 (2014).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
20	15	10	10

Author's contribution: part of XRD experiment and analysis.

[3] Interband absorption edge in the topological insulators Bi2(Te1−x Sex)3 , A. Dubroka, O. Caha, M. Hronček, P. Friš, M. Orlita, V. Holý, H. Steiner, G. Bauer, G. Springholz, and J. Humlíček, Phys. Rev. B 96, 235202 (2017).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
15	15	10	10

Author's contribution: XRD experiment and analysis, contribution to manuscript writing.

[4] Non-magnetic band gap at the Dirac point of the magnetic topological insulator (Bi1−xMnx)2 Se3 , J. Sánchez-Barriga, A. Varykhalov, G. Springholz, H. Steiner, R. Kirchschlager, G. Bauer, O. Caha, E. Schierle, E. Weschke, A. A. Uenal, S. Valencia, M. Dunst, J. Braun, H. Ebert, J. Minar, E. Golias, L. V. Yashina, A. Ney, V. Holý, and O. Rader, Nature Communications 7, 10559 (2016).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
10	5	10	5

Author's contribution: XRD experiment and analysis, contribution to ARPES and XMCD measurements, contribution to manuscript writing.

[5] Structural and electronic properties of manganese-doped Bi_2Te_3 epitaxial layers, J. Růžička, O. Caha, V. Holý, H. Steiner, V. Volobuiev, A. Ney, G. Bauer, T. Duchoň, K. Veltruská, I. Khalakhan, V. Matolín, E. F. Schwier, H. Iwasawa, K. Shimada, and G. Springholz, New J. Phys. 17, 013028 (2015).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
25	20	20	25

Author's contribution: XRD, X-ray absorption spectroscopy, manuscript writing.

[6] Large magnetic gap at the Dirac point in Bi_2Te_3/$MnBi_2Te_4$ heterostructures, E. D. L. Rienks, S. Wimmer, J. Sánchez-Barriga, O. Caha, P. S. Mandal, J. Růžička, A. Ney, H. Steiner, V. V. Volobuev, H. Groiss, M. Albu, G. Kothleitner, J. Michalička, S. A. Khan, J. Minár, H. Ebert, G. Bauer, F. Freyse, A. Varykhalov, O. Rader, and G. Springholz, Nature 576, 423 (2019).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
15	10	10	10

Author's contribution: XRD experiment and analysis, x-ray absorption spectroscopy, transport measurement, preparation of some TEM samples, contribution to manuscript writing.

[7] Mn-Rich $MnSb_2Te_4$: A Topological Insulator with Magnetic Gap Closing at High Curie Temperatures of 45–50 K, S. Wimmer, J. Sánchez-Barriga, P. Kuppers, A. Ney, E. Schierle, F. Freyse, O. Caha, J. Michalička, M. Liebmann, D. Primetzhofer, M. Hoffman, A. Ernst, M. M. Otrokov, G. Bihlmayer, E. Weschke, B. Lake, E. V. Chulkov, M. Morgenstern, G. Bauer, G. Springholz, and O. Rader, Advanced Materials 2021, 2102935 (2021).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
10	5	8	5

Author's contribution: XRD experiment and analysis, x-ray absorption spectroscopy, transport measurement, preparation of TEM samples, and contribution to TEM analysis and manuscript writing.

[8] Topological quantum phase transition from mirror to time reversal symmetry protected topological insulator, P. S. Mandal, G. Springholz, V. V. Volobuev, O. Caha, A. Varykhalov, E. Golias, G. Bauer, O. Rader, and J. Sánchez-Barriga, Nature Communications 8, 968 (2017).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
12	8	10	8

Author's contribution: XRD experiment and analysis, contribution to ARPES experiments, contribution to manuscript writing.

[9] Giant Rashba Splitting in $Pb_{1-x}Sn_xTe$ (111) Topological Crystalline Insulator Films Controlled by Bi-Doping in the Bulk, V. V. Volobuev, P. S. Mandal, M. Galicka, O. Caha, J. Sánchez-Barriga, D. Di Sante, A. Varykhalov, A. Khiar, S. Picozzi, G. Bauer, P. Kacman, R. Buczko, O. Rader, and G. Springholz, Advanced Materials 29, 1604185 (2017).

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
10	8	10	5

Author's contribution: XRD experiment and analysis, contribution to ARPES experiment, contribution to manuscript writing.