Oponentský posudek disertační práce

Autor: **Kristupas Kazimieras Tikuišis**
Název práce: **Optical and magneto-optical properties of topological and Dirac materials**
Studijní program a obor: **Quantum Optics and Optoelectronics, Institute of Physics of Charles University: Department of Optoelectronics and Magneto-optics, Prague**
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Jméno a tituly oponenta: **Artur Slobodeniuk, Ph.D.**
Pracoviště: **Katedra fyziky kondenzovaných látek, MFF UK Praha**
Kontaktní e-mail: **aslobodeniuk@karlov.mff.cuni.cz**

Odborná úroveň práce:

❑vynikající ☒ velmi dobrá ❑ průměrná ❑ podprůměrná ❑ nevyhovující

Věcné chyby:
❑ téměř žádné ☒ vzhledem k rozsahu přiměřený počet ❑ méně podstatné četné ❑ závažné

Výsledky:
☒ originální ❑ původní i převzaté ❑ netriviální kompilace ❑ citované z literatury ❑ opsané

Rozsah práce:
❑ veliký ☒ standardní ❑ dostatečný ❑ nedostatečný

Grafická, jazyková a formální úroveň:
❑ vynikající ☒ velmi dobrá ❑ průměrná ❑ podprůměrná ❑ nevyhovující

Tiskové chyby:
❑ téměř žádné ☒ vzhledem k rozsahu a tématu přiměřený počet ❑ četné

Celková úroveň práce:
❑ vynikající ☒ velmi dobrá ❑ průměrná ❑ podprůměrná ❑ nevyhovující

Slovní vyjádření, komentáře a připomínky oponenta:

Thesis of Kristupas Kazimieras Tikuišis “Optical and magneto-optical properties of topological and Dirac materials” is dedicated to the study of the special class of (semi)conducting materials which electronic excitations (quasiparticles) can be described by Dirac type Hamiltonians. The current investigation is focused on two typical representatives of such condensed matter systems: graphene and lead tin salts with chemical formula $Pb_x Sn_{1-x}Se$.

The low-energy band structure of graphene is described by a pair of two-dimensional Dirac Hamiltonians (each Hamiltonian describes the electronic excitations in two non-equivalent K and $-K$ valleys, respectively). The Hamiltonians contain only two parameters: band gap E_g (for the

general case of the graphene placed on the substrate) and Fermi velocity $v_F \approx c/300$, where c is the speed of light in a vacuum. Such a simple parameterization makes this material an ideal model system for non-invasive (magneto-)optical studies. The lead-tin salts ($Pb_x Sn_{1-x}Se$) represent another example of Dirac-type materials. Their crystals are characterized by rock salt structure. The band gap minima of these crystals are localized in 8 high-symmetric so-called L-points of the first Brillouin zone. The electronic excitations near these points are described by three-dimensional Dirac-type Hamiltonian. Unlike to graphene, the Hamiltonian of $Pb_x Sn_{1-x}Se$ compound contains more parameters than just E_g and v_F. The minimal model for these materials contains two additional parameters – M and C. They define spin-dependent and spin-independent corrections to the curvature of the valence and conduction bands, respectively. It turns out that the properties of the corresponding material strongly depend on the sign of the M parameter. For $M > 0$, the band structure, defined by the Hamiltonian, is trivial, i.e. it is the same as in conventional semiconductors, while for $M < 0$ the bands are inverted. For the latter case, the system should demonstrate unusual electronic properties, due to appearing topologically protected surface states. The study of such materials in the topological phase is important from a fundamental as well as from a practical point of view. **Investigation of the electronic and (magneto-) optical properties of Dirac-type materials is a valuable topic of modern condensed matter physics. Therefore the study of graphene and lead-tin salts, provided in the current thesis, is relevant, important, and timely.**

The core part of the thesis contains 5 chapters and the "Summary and conclusions". Chapter I gives an introduction to the topic of the Dirac materials. Chapter II provides a characterization of the physical properties of lead-tin salts and graphene as Dirac materials. Chapter III introduces a detailed description of the experimental methods – spectroscopic ellipsometry and magneto-optical spectroscopy – used for the investigation of the aforementioned materials. Chapter IV consists of three big sections: theoretical, sample preparation and characterization, and experimental. The theoretical section provides a) the full theoretical description of the Hamiltonian of bulk $Pb_xSn_{1-x}Se$ and its comparison with the conventional topological Hamiltonian of Bi_2Se_3; b) analysis of the eigenstates of the $Pb_xSn_{1-x}Se$ Hamiltonian; c) optical selection rules for interband optical transitions in the presence of a magnetic field in such crystals. The second section gives a detailed description of the samples preparation and their characterization. The experimental section contains a description of the magneto-optical measurements and the systematic analysis of the obtained experimental data. Among them one can highlight a) the magnet transmission analysis confirms the applicability of the Dirac-type Hamiltonian for the description of the low-energy structure of the lead-tin salt crystals; b) allowed to estimate the values of the band gaps and Fermi velocities in these crystals; c) The chapter V describes the optical measurements of the epitaxial graphene and provides the analysis of the obtained spectroscopic data. **Note that, chapters IV and V provide the original results of optical and magneto-optical studies of considered Dirac-type materials demonstrating the author's ability for creative scientific work.**

The text of the thesis is well-written and contains a good graphical representation of the discussed subject. Unfortunately, there are some errors and typos in the thesis. Most of them are presented in the first three chapters of the thesis and, fortunately, don't affect the results and conclusions, provided in the last two chapters of the thesis. **Therefore, I can't classify the work as "vynikající", but it can be considered as "velmi dobrá" from my point of view.**

Případné otázky při obhajobě a náměty do diskuse:

Otázky:

1. The Hamiltonian (2.45) is a tight-binding Hamiltonian of graphene where next-nearing neighbors are taken into account. The author didn't explain the importance of next-

neighbor atoms for the spectrum of electrons in graphene and why he chose the particular relations between the coupling constant of the leading term t and the coupling constant $t' = -0.2t$ of the next-nearest neighbor terms. Can the author explain a) why he considers the Hamiltonian in the form of equation (2.45) and b) explain the origin of the linear relation between the hopping parameters t and t'?

2. I think that the formula (4.64) for the spectrum of the Dirac-type Hamiltonian for $Pb_x Sn_{1-x}Se$ in a magnetic field for the particular case of $C = 0$ is incorrect. Despite the fact that this general formula is not used in further analysis of the experimental data and hence this result doesn't affect the original conclusions about the properties of $Pb_x Sn_{1-x}Se$, this wrong formula spoils the impression of the text in general. How can the author of the thesis comment on this wrong formula and its derivation?
3. There is a discussion of the results of T. Ando et al. (see the bottom of page 20 and the top of page 21) for the expression of the conductivity of graphene at zero frequency. Their result doesn't coincide with the equation (2.50). Can the author comment on these different results? Which formula is finally correct?

Překlepy a drobné komentáře:

- Typo in the formula (2.10), the last Pauli matrix should be σ_z.
- Lost "i" in the exponent in the formula (2.14).
- Lost „u_p" in the equations (2.16) and (2.17).
- The derivation of the formula (3.59) is not clear for general reader.
- There is a typo in the formula (4.38), should be l_B in the denominators of the expressions for q_x and q_y.
- There are two typos in the Hamiltonian (4.44): a) should be the annihilation operator a in the low left corner of the matrix instead of the creation operator $a^\dagger$; b) the parameter A_0 in the upper right corner of the matrix should be removed.
- The expression (4.50) should have $(C - M)$ term in the numerator instead of $(C + M)$.
- There are two different paramaters C in the formula (4.60), bad notation.
- There is a typo in the equation (4.63), should be $-8\lambda ABC$ instead of $-4\lambda ABC$

Práci
☒ doporučuji
❑ nedoporučuji
uznat jako disertační.

Místo, datum a podpis oponenta: v Praze 19 . července 2023