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Transport processes in two-dimensional nanostructures

Thesis statements

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In my PhD thesis I investigated three loosely-connected problems with theoretical methods which are linked by one common bond: all of them are related to the transport properties of two-dimensional systems. My results presented in the thesis can be summarized in four thesis statements, which can be grouped around these three topics. The numbers in the square brackets after each statement refer to my publications related to the topic.

Diverging dc conductivity in two-dimensional nanosystems of pseudospin-1

In the first chapter I studied crystals with electronic structure whose effective mathematical model is the two-dimensional massless pseudospin-1 Dirac-Weyl equation; an example of such crystals is the dice or $\mathcal{T}_3$ lattice. The band structure of these systems consists of three bands touching each other at the charge neutrality point: two bands forming Dirac cones have linear dispersion similar to graphene, while the third is a dispersionless flat band with zero energy. I investigated the dependence of the density of states (DOS) and the dc conductivity on the strength of the short range disorder. The following thesis statement is related to this topic:

1. For the two-dimensional dice lattice (also known as $\mathcal{T}_3$ lattice) I showed with numerical calculations (based on the tight binding model and the kernel polynomial method) that the sharp peak in the DOS of the clean system corresponding to the dispersionless flat band broadens in the presence of short-range disorder. The width of this peak is proportional to the strength of the scatterers, while the height of the peak is inversely proportional to it. With the numerical evaluation of the Kubo formula I demonstrated that at the charge neutrality point the dc conductivity increases logarithmically with decreasing disorder. The agreement between my numerical calculations and the results based on the continuous model and diagram technique is good, and can be improved by reducing the finite-size effects (i.e. increasing the size of the lattice). [T1]

Investigation of Kerr and Faraday rotation in layered nanostructures with the transfer matrix method

In the second part of the thesis I studied the optical properties of multilayer structures consisting of atomically thin conducting layers and dielectrics, with special regard to ellipsometric characteristics. The following two thesis statements are related to this topic:

2. Starting from Maxwell's equations I presented a systematic, modular method based on transfer matrices for calculating the Kerr and Faraday rotation of multilayers consisting of atomically thin conducting layers and dielectrics for arbitrary angle of incidence and polarization. The method can be efficiently used for designing ellipsometry experiments in which the goal is to measure the Hall conductivity of the atomically thin layer. [T2]

3. In view of the conductivity tensor of the bilayer graphene calculated from a four-band model I proposed a few experimental arrangements of different geometry, with which the quantum anomalous Hall state of the bilayer graphene can be identified by measuring the Kerr angle. I showed that choosing the appropriate width of the substrate can significantly enhance the Kerr rotation. [T2]

Investigation of Landau levels in silicene dots and antidots

In the last chapter Landau states in circular silicene quantum dots (disks) and antidots (holes) were investigated in the presence of perpendicular magnetic field. My results are summarized in the following thesis statement:

4. I derived analitical formulae for the eigenstates of circular silicene dots and antidots placed in perpendicular magnetic field in the framework of the continuous model. By solving these equations numerically the Landau levels can be calculated. I showed that due to the significant intrinsic spin-orbit coupling in silicene, protected edge states are present in the system which are localized to the perimeter of the dot/antidot and polarized in valley-spin pairs. The energy of these states lies inside the bulk band gap. I found that these edge states carry circular currents flowing in opposite directions corresponding to their valley and spin index. [T3]

Publications related to the thesis statements:

[T1] M. Vigh, L. Oroszlány, S. Vajna, P. San-José, G. Dávid, J. Cserti, B. Dóra: *Diverging dc conductivity due to a flat band in a disordered system of pseudospin–1 Dirac-Weyl fermions*, Phys. Rev. B **88**, 161413(R) (2013)

[T2] G. Széchenyi, M. Vigh, A. Kormányos, J. Cserti: *Transfer matrix approach for the Kerr and Faraday rotation in layered nanostructures*, Journal of Physics: Cond. Mat., Vol. **28**, No. 37 (2016)

[T3] P. Rakyta, M. Vigh, A. Csordás, J. Cserti: *Protected edge states in silicene antidots and dots in magnetic field*, Phys. Rev. B **91**, 125412 (2015)

Books (not related to the field):

[K1] Gnädig P., Honyek Gy., Vigh M.: *333+ Furfangos Feladat Fizikából*, (second, extended edition) TypoTeX (2017)

[K2] P. Gnädig, G. Honyek, M. Vigh: *200 More Puzzling Physics Problems*, Cambridge University Press (2016)

[K3] Gnädig P., Honyek Gy., Vigh M.: *333 Furfangos Feladat Fizikából*, TypoTeX (2014)

Other international publications (not related to the field):

[E1] M. Vigh, P. Gnädig, G. Honyek: *Funny motions of billiard balls*, A. Király, T. Tél (ed.): Teaching Physics Innovatively: New Learning Environments and Methods in Physics Education, 305–310 (2016)

[E2] H. J. Kwee, O. Gunawan, Y. Surya, M. Vigh: *The final round of the first World Physics Olympiad held in Lombok, West Nusa Tenggara, Indonesia: a sample of problems and solutions and student results*, Eur. J. of Phys. **34**, 4 (2013)