Modeling the distribution line form of surface electromagnetic wave and calculating the transmission coefficient of a symmetric strip line

O B Gladkikh and I I Vasilyeva

Department of mathematical modeling and computer technologies, Yelets State University of I A Bunin, Kommunarov str., 28, Yelets, Lipetsk region, 399770, Russia

E-mail: og1972@rambler.ru

Abstract. The work is devoted to the analysis of the dependence of the dielectric properties of highly conducting anisotropic materials from the magnitude and the direction of the magnetic field. A nonlinear model of propagation of a surface electromagnetic wave in a planar bismuth waveguide located in a quantizing magnetic field is considered. As a result of the simulation of the shape of the magneto-optical experiment line, a software package in the JavaScript language for calculating the dielectric constant and the bismuth conductivity tensor for each direction (binary, bisector and trigonal) is presented.

1. Introduction

The bismuth crystal structure is the arsenic type lattice with two atoms per unit cell. Due to crystal inversion symmetry and time reversal symmetry, all the bands are doubly degenerate throughout the Brillouin zone for zero magnetic field [1].

Each of the three electron Fermi surfaces is close in shape to an ellipsoid with the ratio of major to minor axes approximately 15:1. The principal axes of an electron Fermi surface are rotated about the binary axis by approximately +6° from the BBT system, that is, k_x is parallel to the binary axis, k_y makes an angle of about 6 degrees to the bisectrix axis, and k_z makes an angle 6 degrees to the trigonal direction. The three electron Fermi surfaces

2. Modeling

Though there has been a great deal of study of the electronic properties of bismuth, the present theoretical understanding is quite inadequate. It was only recently that the confusion concerning the relationships among the principal energy band models was cleared up. Though the shapes of the Fermi surfaces and their locations within the Brillouin zone have been determined, the overall numerical agreement between theory and experiment is quite poor [2].

In the past work results of modeling of the form of an experimental line of magneto optical experiment in extreme quantum limit of a magnetic field are presented. The account in mathematical model of dependence of energy of levels of Landau with small values of quantum numbers from a magnetic field and a wave vector has allowed to classify observable magneto optical features, to define the contribution of each electronic transition, occurrence saddle points in a power spectrum of alloys
bismuth-antimony and to prove presence along with resolved the considerable contribution of the forbidden transitions to extreme quantum limit of a magnetic field [3].

![Figure 1. Transmission of symmetric stripe line of bismuth.](image1)

In the present work we present modeling of the lattice dielectric permittivity for electrons and holes showed, that the best fitting there is then there is one value of the lattice dielectric permittivity for electrons and other – for holes. [4] Behavior of the relaxation time from magnetic field is similar with dependence of the lattice dielectric permittivity from magnetic field.

![Figure 2. Results of modeling of the form line of magnetooptical experiment when the magnetic field is oriented along binary axis.](image2)

Numerical calculations can come to errors or to mistakes in determination of the roots of the dispersion equation. The sensitivity of the results of numerical calculations to initial guess of solution permits us to form an opinion about stability of the solution and indirect about correctness our numerical procedure [5].

![Program for calculating the characteristics of a strip line in the binary direction.](image3)

In this work, the modeling of the line shape of the magneto-optical experiment consisted in the numerical calculation of the transmission coefficient of the transmission coefficient of a symmetric
The calculation algorithm assumed the solution of the system of Maxwell equations with boundary conditions:

\[
\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \ \vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + j \vec{B}\vec{B} = 0, \vec{\nabla} \vec{D} = \rho.
\]  

(1)

Where \( \vec{E}, \vec{B}, \vec{D}, \vec{H} \) - vectors of intensity and induction of electric and magnetic fields, \( \vec{\nabla} \) - gradient operator.

As a result, a formula was obtained for calculating the transmission coefficient of a symmetric strip line by numerical methods:

\[
T = 2.27 \cdot e^{2L \cdot [\text{Im}(q_y(B)) - \text{Im}(q_y(0))]}.
\]

(2)

The nonlinear model of distribution of surface electromagnetic wave in a planar waveguide out of bismuth located in the quantizing magnetic field at a temperature of liquid helium is considered. The dispersing equation of a wave for each direction is removed (binary, bisector and trigonal). The formula for calculation of passing of submillimeter radiation through the symmetrical strip line depending on value of a magnetic field is obtained. The algorithm of the numerical solution by means of a script programming language JavaScript is offered and the accompanying applications for digitization of the experimental data in graphical form are developed [7].

**Figure 4.** Modeling of the lattice dielectric permittivity for electrons and holes.

Experimental results demonstrate a variety of structures in ultraquantum limit of the magnetic field. We have to consider the model of interacting the Landau levels of the valence band and conduction band with quantum numbers \( j = 0 \). It makes it possible to introduce additional degrees freedom to exercise the ability to fit model spectra to experimental ones. In our consideration, we limited ourselves to considering the second of a higher order of perturbation theory. As a result, the masks of the matrix elements of the velocity operator have a complex and pronounced dependence on magnetic field [8].
Figure 5. Dependence of the intensity of the radiation transmitted through the strip line on the value magnetic field.

3. Conclusion
The received results allow to apply this technique to a wide class of research problems and can be used for creation of the active waveguide environments on the basis of the balanced strip line, controlled by a magnetic field.

The nonlinear model of the propagation of a surface electromagnetic wave in a planar bismuth waveguide constructed in this work can be used to create active waveguide media based on a symmetric strip line controlled by a magnetic field, as well as in mathematical modeling of high-tech systems.

References
[1] McClure J W and Choi K H Energy Band Model and Properties of Electrons in Bismuth 1977 *Solid State Communications* **21** 1015-8
[2] Choi K H 1978 *Calculation of Landau Levels and Electronic Properties of Bismuth* (Diss. doct. of phil) p 128
[3] Lax B, Mavroides J G, Zeiger H J and Keyes R I Infrared Magnetoreflection in Bismuth 1960 *Phys. Rev. Lett.* **5(6)** 241-3
[4] McClure J W The Energy Band Model for Bismuth: Resolution of a Theoretical Discrepancy 1976 *J. Low Temp. Phys.* **25(5/6)** 527-40
[5] Vasilyeva I I and Masina O N Features of The Study of The Band Structure of Bismuth 2014 *International Academic Bulletin* **1** 45–51
[6] Vasilyeva I I 2014 Modeling of a Magneto-optical Experiment in Bismuth Based on The Calculation of The Transmittance (All-Russian conference with international participation "Information and telecommunication technologies and mathematical modeling of high-tech systems" **28th International Conference on the Physics of Semiconductors, November 10–14, 2014, Ufa, Russia, Conference Proceedings) p 292-306
systems" Moscow RUDN April 22-25)
[7] Vasilyeva I I and Gladkikh O B An Approach to Finding The Parameters of Propagation of a Surface Electromagnetic Wave Based on Numerical Modeling Methods 2018 Science-intensive technologies 5(19) 49-55
[8] Vasilyeva I I and Gladkikh O B Program for calculating the dielectric constant tensor of bismuth 2018 Pat. of the Russian Federation No 2018617902 appl. 06.04.2018, publ. 03.07.2018