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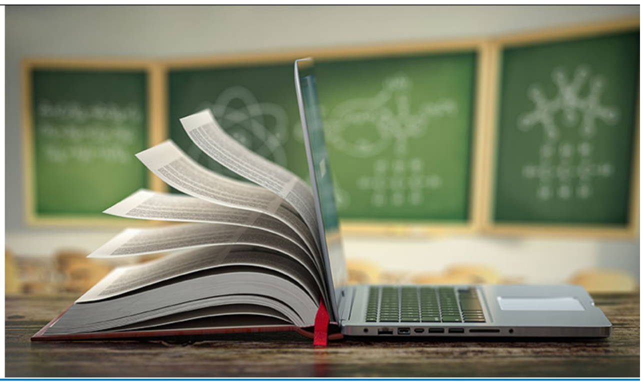

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Size effect in the kinetic properties in "sized" films of Bi_2Se_3 topological insulator

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Abstract. The Hall resistivity and magnetoresistivity of topological insulator Bi_2Se_3 thin films with a thickness from 30 nm to 75 nm in the temperature range from 4.2 to 80 K and magnetic fields of up to 10 T were measured. A size effect in the kinetic properties of bismuth selenide films was studied, i.e. a dependence of the Hall coefficient and magnetoconductivity of film dimensions. It was suggested that a similar size effect should be observed in other kinetic electronic properties, both of topological insulators and topological semimetals.

1. Introduction

The search and study of new quantum materials with unusual physical properties is one of the urgent problems of modern physics and materials science. Topological materials, namely topological insulators (TI) [1-3], belong to this class of materials.

Topological insulators were predicted in 1970 year [1], and they exhibit unique physical properties. The TI bulk is an insulator or semiconductor, and the surface behaves like a topologically protected metal. Moreover, its dispersion law is linear, and the charge carriers in this "surface" layer are spin-polarized [2, 3], which can be used in spintronics. Earlier in [4] it was reported that due to the large difference in the conductivity of the bulk and surface of the TI, a “size” effect arises in the electrical resistivity, when the conductivity of the sample depends on its size and shape [4].

The presence of such unique surface states in TIs makes them promising materials for the creation of electronic devices with a high response rate and low power consumption, as well as in spintronics. However, it is not so easy to use it in practice, because in real materials with TI properties, the total conductivity is determined not only by "surface" current carriers, but also by "bulk" ones. The point is that the bulk in such TIs is more likely a semiconductor than a good dielectric. Therefore, the problem arises of “separating” the surface and bulk conductivities and taking into account their partial contributions, which must be consider when developing devices operating on the basis of TI.

Since the bulk and surface conductivities of a TI are very different, in such materials an inhomogeneous flow of electric current over the conductor cross section can occur. A similar effect, i.e. non-uniform distribution of electric current in a conductor, observed in pure compensated metals with a skin effect on direct current [5]. So, in [6] the size effect was found in the conductivity of tungsten in strong magnetic fields, i.e. the dependence of magnetic conductivity (magnetoresistivity) on the cross-section of the conductor. Since a low current density in the bulk and an increased one near the surface should also be observed in TIs, the size effect, that is the dependence of the electronic kinetic properties of the sample on its size, should be observed in TIs as well.

It is known that the size effect is also found in other transport properties of TIs. For example, the authors of [7] observed the size effect in the number of transport channels in TI Bi_2Se_3 thin films grown by magnetron sputtering. The size effect in the mobility and density of charge carriers in TI Bi_2Se_3 films was studied in [8].

In [4, 9], it was reported about the observation of the size effect in the electrical conductivity of Bi_2Se_3 thin films; the dependence of the conductivity on the reciprocal thickness of Bi_2Se_3. It is logical to assume that a similar effect should be observed in other kinetic electronic properties of Bi_2Se_3, in particular, in the Hall Effect. Therefore, the aim of this work is to search for and study the size effect in the Hall Effect of Bi_2Se_3 films.

2. Experimental

Thin films of the Bi_2Se_3 topological insulator with a thickness from 30 nm to 75 nm were chosen as the object of research. This choice was due to the fact that, firstly, this material is a 3D TI, and secondly, it was in it that the size effect was observed in the conductivity and the number of transport channels [4, 7, 9]. To obtain the films, the method of molecular beam epitaxy was used. Structure characterization was performed using XRD and SEM with the EDAX attachment. Details of sample growth and structure characterization are described in [10, 11].

The electro- and magnetoresistivity, as well as the Hall Effect were measured by the conventional 4-points method at dc-current (see [4, 9]) with commutation of the direction of the electric current through the sample, and in the case of the Hall Effect, also with commutation of the direction of the magnetic field relative to the film plane. The magnetic field vector was directed perpendicular to the film surface. The measurements were carried out in the temperature range from 4.2 to 80 K and in magnetic fields of up to 10 T. The results are presented in units of conductivities $\sigma_0 \approx 1 / \rho_0$, $\sigma_{xx} \approx \rho_{xx} / (\rho^2_{xx} + \rho^2_{xy})$, $\sigma_{xy} \approx \rho_{xy} / (\rho^2_{xx} + \rho^2_{xy})$ and Hall coefficient $R_H = \rho_{xy} / B$. Some of the results are presented as a change in conductivity in a magnetic field, i.e. $\Delta\sigma_{xx} / \sigma_0 = (\sigma_{xx} - \sigma_0) / \sigma_0$.

3. Results and discussion

In [4], a size effect was found in the conductivity (resistivity) of bismuth selenide films without a magnetic field. Apparently, this effect can also be observed in a magnetic field. Figure 1 shows the temperature dependences of the magnetic conductivity σ_{xx} in a field of 10 T. It is seen (Figure 1) that with decreasing thickness *d* the conductivity increases. It is logical to assume that such a size dependence should be observed in other electronic kinetic properties, namely, in the Hall Effect.

Figure 2 shows the temperature dependences of the Hall conductivity σ_{xy} and the Hall coefficient of bismuth selenide films R_H. As can be seen from Figure 2, the values of the modulus of the Hall resistivity and the Hall coefficient also depend on the thickness of the films, the absolute values of σ_{xy} decreases, and R_H increases with increasing thickness *d*.

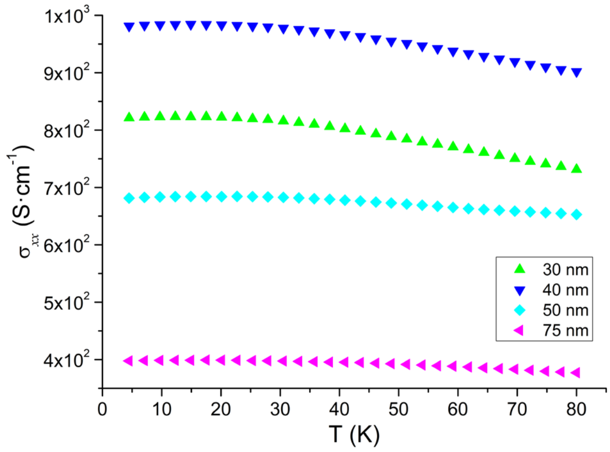
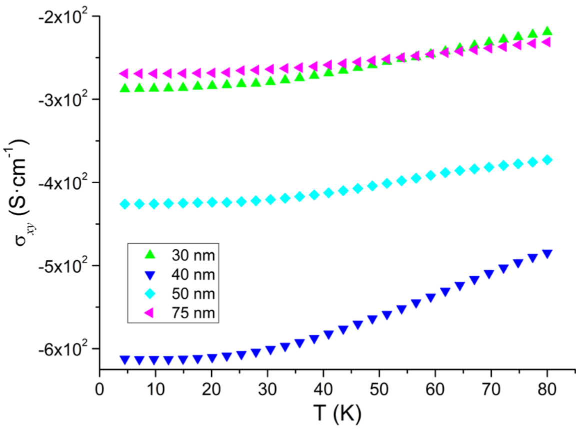


Figure 1. Temperature dependence of conductivity in magnetic field of 10 T of TI Bi_2Se_3 films.



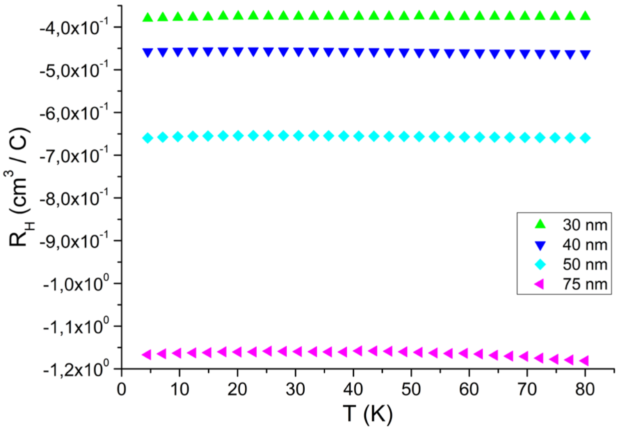


Figure 2(a, b). (a) Temperature dependence of Hall conductivity of TI Bi_2Se_3 films; **(b)** Temperature dependence of Hall coefficient of TI Bi_2Se_3 films.

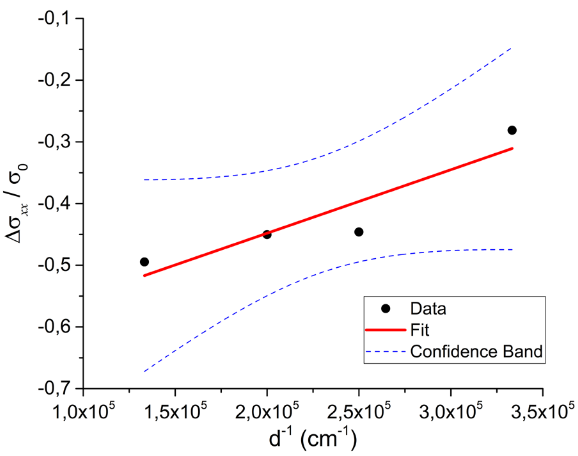
In [4, 9], it was demonstrated that the conductivity σ_0 of thin films of bismuth selenide without a magnetic field is directly proportional to the reciprocal thickness d of the sample, i.e. $\sigma = f(d^{-1})$. Apparently, such a dependence should appear in the electronic kinetic properties in a magnetic field, i.e. in magnetoconductivity and Hall Effect. It was shown in [4] that the conductivity σ of such a system can be written as:

$$\sigma \approx \sigma_s \cdot \frac{\delta}{d} + \sigma_b , \tag{1}$$

where σ_s is a surface conductivity of the near-surface layer with a thickness of δ, σ_b is a bulk conductivity.

The first term in Equation (1) is proportional to surface conductivity σ_s and second one is the bulk conductivity σ_b, which makes it possible to "separate" the surface and bulk contributions. Considering the data in [12], the estimation value of delta is not more than 2 nm.

Figure 3a shows the dependence of the magnetoconductivity versus d at T = 4.2 K. One can see that there is a fairly good agreement between the calculation and the experiment. A similar dependence for the Hall coefficient is observed (Figure 3b).



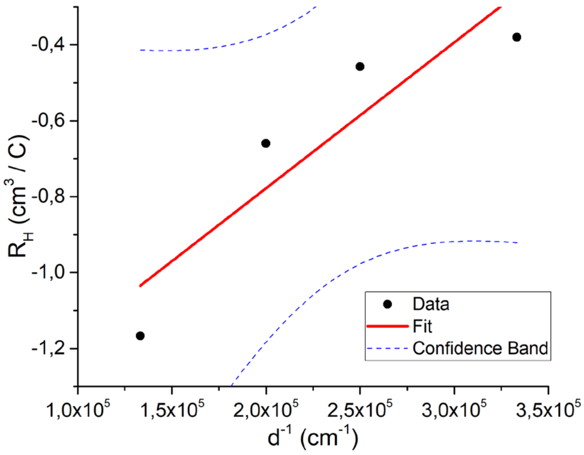


Figure 3(a, b). (a) Size effect in the magnetoconductivity of Bi_2Se_3 at 4.2 K; **(b)** Size effect in the Hall coefficient of Bi_2Se_3 at 4.2 K.

It is also necessary to point out that with increasing temperature, the linearity of the experimental dependence worsens; however, even at 80 K, the experimental points are in the confidence band of the used mathematical model.

According to evaluations, bulk contribution of magnetoconductivity ~ -0.65 and surface one ~ 5.2; bulk contribution of Hall coefficient ~ -1.55 cm^3/C and surface one ~ 19.22 cm^3/C at T = 4.2 K. That means the surface contribution of kinetic coefficients more than one order of magnitude higher than bulk contribution at the temperature of 4.2 K. The obtained results are in good qualitative agreement with the Ref. [13]. The "-" sign in bulk magnetoconductivity means that the conductivity (resistivity) decreases (increases) with increasing magnetic field. On the contrary, surface conductivity (resistivity) increases (decreases) with a magnetic field, therefore it is positive.

It is known [14] that the Hall Effect in bulk materials with a complex Fermi surface is determined by contributions from various types of current carriers belonging to different sheets of the Fermi surface. In the case of compensated conductors (see, for example, [15, 16]), the Hall Effect mainly depends on the scattering processes and differences in the mobilities and effective masses of individual groups of charge carriers. Apparently, the "surface" Hall Effect in Bi_2Se_3 films is determined by holes; therefore, the "surface" Hall coefficient is > 0, and the main contribution to the "bulk" Hall Effect is formed by electrons and the "bulk" Hall coefficient < 0. However, this is only the simplest qualitative an explanation of the observed effect, which requires further research.

To obtain the temperature dependences for the bulk and surface contributions to the total magnetic conductivity and to the Hall coefficient, it is necessary to plot the graphs shown in Figure 3 for each temperature from the temperature range and make the corresponding calculations using Equation (1).

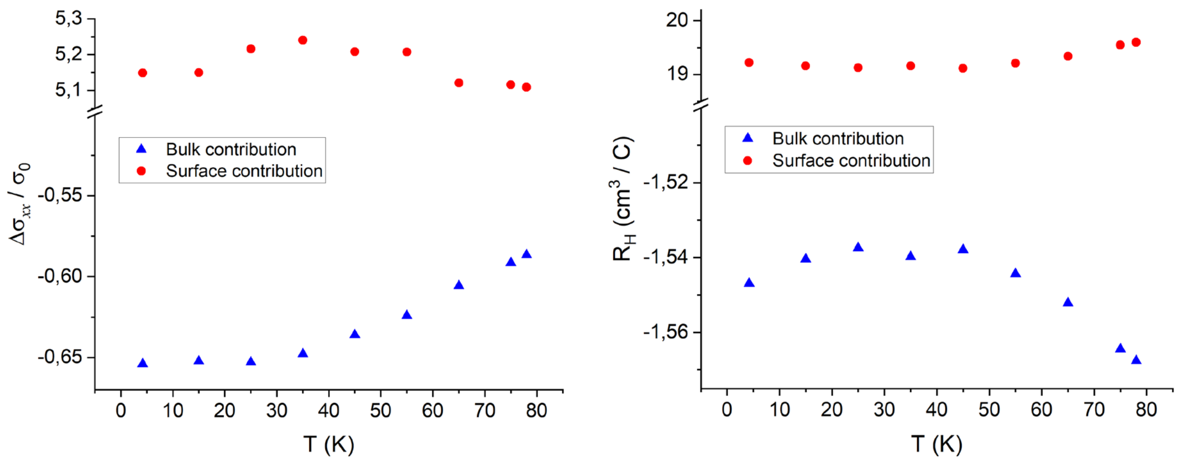


Figure 4(a, b). (a) Temperature dependences of bulk and surface contributions in total magnetoconductivity of TI Bi_2Se_3; **(b)** Temperature dependences of bulk and surface contributions in total Hall coefficient of Bi_2Se_3 in magnetic field 10 T.

Figure 4a shows the magnetoconductivity (MC) of the bulk and surface of bismuth selenide films in magnetic field of 10 T. It can be seen that the MC of the bulk increases with *T*, and the MC of the surface is almost independent of *T*. An increase in the bulk MC can be explained by the fact that, with increasing *T*, the main contribution to the MC of the bulk comes from electron-phonon scattering. Surface metallic states are topologically protected and the processes of electron-phonon scattering have little effect on the surface conductivity, at least in the temperature range from 4.2 to 80 K. Values of surface MC and bulk MC differ significantly, exactly, they differ by 8 times.

It can be seen (Figure 4b) that the surface Hall coefficient, as well as the surface conductivity, varies slightly with temperature, while the bulk Hall coefficient decreases with temperature (or increases in absolute value). This behavior of the Hall Effect can be qualitatively explained in this way. Since surface current carriers in TI are topologically protected, scattering processes near the surface are also forbidden, which is manifested in the independence (or weak dependence) of the Hall coefficient on temperature. On the contrary, carrier scattering in the TI bulk leads to the fact that the contribution to the Hall mobility and, consequently, to the Hall coefficient of electrons becomes more predominant in comparison with the hole contribution. This leads to the temperature dependence of the Hall coefficient. However, further experimental and theoretical studies are required to quantify this behavior of the Hall Effect in TIs.

4. Conclusions

Thus, the study of the kinetic electronic properties of Bi_2Se_3 films revealed the size effect in the magnetoconductivity and the Hall coefficient, i.e. the dependence of magnetoconductivity and Hall coefficient on the thickness of Bi_2Se_3 films. It is demonstrated that the discovered effect can be used to “separate” the bulk and surface contributions to the magnetoconductivity and Hall coefficient in such topological materials. In particular, the difference in the values of the surface and bulk contributions is shown to be very significant and can be more than an order of magnitude, and in a wide temperature range from 4.2 to 80 K. The results obtained are direct evidence of a significant difference in the conductivity of the surface and bulk, i.e. confirmation of the "topological" nature of such materials.

Apparently, a similar size effect should be observed in other kinetic electronic properties of both topological insulators and topological semimetals.

Acknowledgments

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